Buyong, Taher B., Andrew U. Frank, and Werner Kuhn. "A Conceptual Model of Measurement-Based Multipurpose Cadastral Systems." *Journal of the Urban and Regional Information Systems Association URISA* 3, no. 2 (1991): 35-49.

A Conceptual Model of Measurement-Based Multipurpose Cadastral Systems

Taher B. Buyong, Werner Kuhn and Andrew U. Frank

Taher Buyong is a Ph.D. candidate in the Department of Surveying Engineering at the University of Maine. He holds B.S. and M.S. degrees in surveying engineering from the University of New Brunswick and University of Calgary in Canada, respectively. His doctoral research focuses on the development of measurement-based multipurpose cadastre concepts for local governments.

Werner Kuhn is a research associate at the National Center for Geographic Information and Analysis (NCGIA) and cooperating assistant professor at the Department of Surveying Engineering, both at the University of Maine. He holds a Ph.D. and a Dipl. Ing. in Surveying Engineering from the Swiss Federal Institute of Technology (ETH) Zurich, Switzerland. His current research focuses on human interaction with geographic information systems.

Andrew Frank is the New England section ACSM professor in land information studies and an associate professor in surveying engineering at the University of Maine. He received his Ph.D. from the Swiss Federal Institute of Technology (ETH), Zurich, Switzerland and a Dipl. Ing. from the same institute. His research interests include treatment of geometry in computer systems, and the human interface for GIS systems.

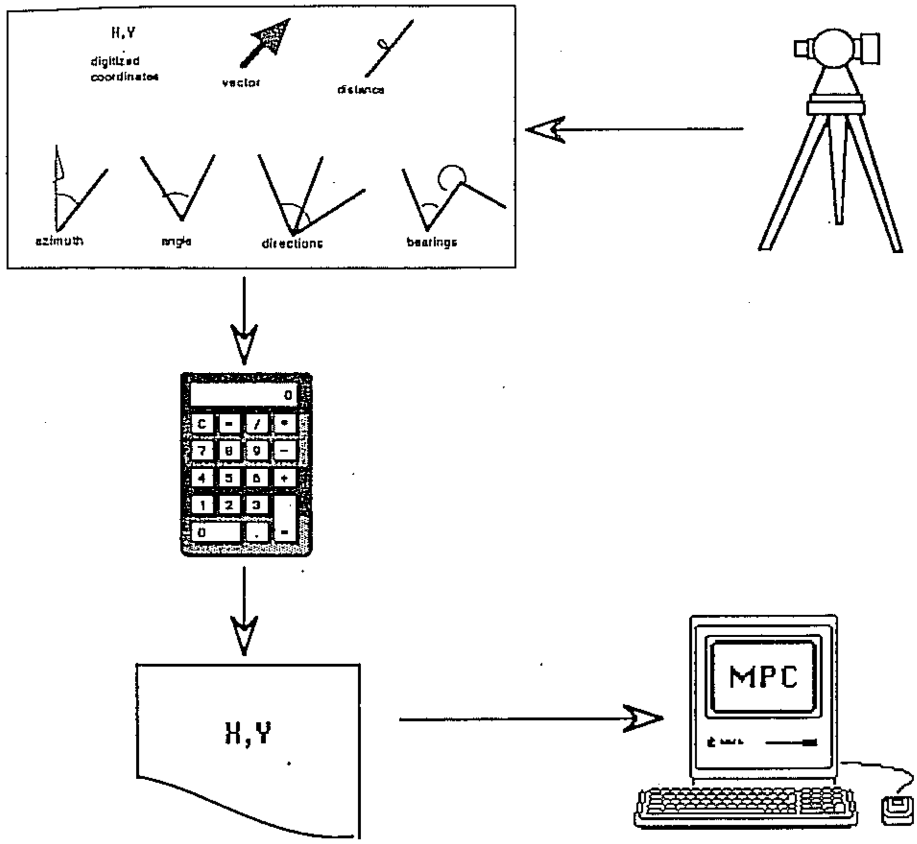
Abstract: *A measurement-based multipurpose cadastral system uses measurements as the basic carrier of metric information. This concept is realized by allowing the processing of the measurements to be suspended until metric information is needed. Least squares adjustment is the tool used to process the measurements and a direct manipulation user interface provides appropriate interaction with the system. A measurement database furnishes convenient management of measurements and related data. The advantages of a measurement-based system include incremental implementation, ease of updating, improvement of accuracy over time, correct integration of different data layers, and preservation of background information.*

A multipurpose cadastral system is a framework that supports comprehensive land-related information such as land use, vegetation, buildings, mineral resources, flood hazards, utilities, income, and population at the parcel level. It uses a cadastre as the basic building block. A cadastre is a complete and up-to-date official register or inventory of land parcels in any jurisdiction containing information about the parcels regarding their locations and extensions, and other pertinent data such as ownerships, rights, uses, and valuations (Dale and McLaughlin 1988; NRC 1983).

Parcel corners are first used to define the geometry of the parcels. Later, they are used together with other points which have unique spatial positions to link and correctly register land-related data such as soil type, vegetation, topography, hydrology, and utility data. All these different types of data which make up a multipurpose cadastral system are usually seen as distinct layers superimposed on a cadastral layer (Dale and McLaughlin 1988; NRC 1980). This kind of multipurpose cadastre is based on a set of previously established, and sufficiently complete and accurate geodetic control points.

A study by the United States National Research Council (NRC 1980) indicated that there is a critical need for a better multipurpose cadastral system at each level of government to improve land-conveyance procedures, furnish a basis for equitable taxation, and provide much-needed information for resource management and environmental planning. To assist local level governments in developing multipurpose cadastral systems, the National Research Council later proposed the following implementation steps of a multipurpose cadastral system (NRC 1983):

FIGURE 1.
Measurements are processed and the resulting coordinates are stored in a coordinate-based system.

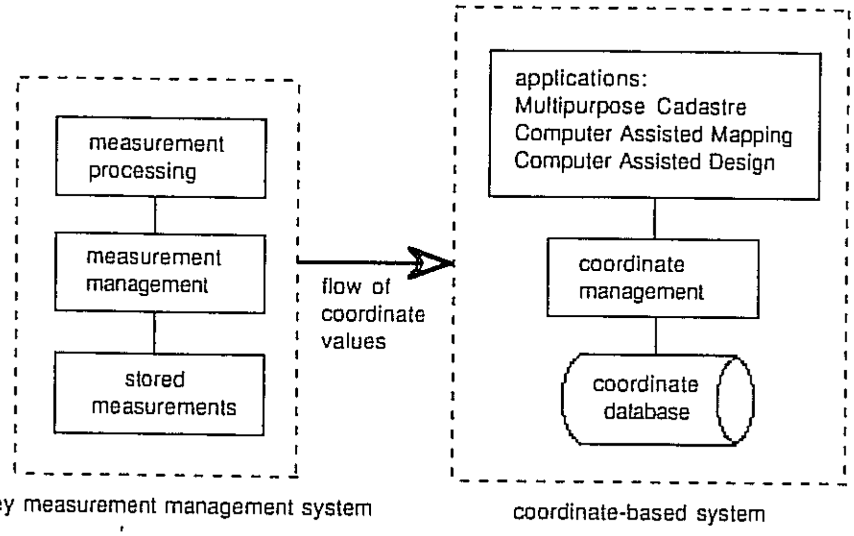


1) establishment of a network of geodetic control points,
2) preparation of the base maps,
3) preparation of the cadastral overlay,
4) maintenance of the parcel-registers and data file; and
5) maintenance of the link between the cadastre and other land-related data.

This amounts to a coordinate-based approach and a system implemented following such procedures is called a coordinate-based cadastral system. The basic idea of coordinate-based systems is illustrated in Figure 1.

Several problems are associated with the above method of implementation because of the segmented nature of the process. First, the sequence of operations as proposed requires a large investment of resources at the beginning and a long wait before benefits are realized from the system. This makes a multipurpose cadastral system proposition difficult to sell in the political arena. A number of attempts to implement a multipurpose cadastral system have met financial difficulties during this initial period (Bauer 1982; Wentworth 1989). Second, a multipurpose cadastre based on an accurate survey at the beginning naturally decays over time

FIGURE 2.
A survey measurement management system as a supporter of a coordinate-based multipurpose cadastral system.



since maintenance of this accurate geometric base which is in the form of coordinates is difficult. As a matter of fact, coordinates are not maintainable; obsolete coordinate values are discarded and replaced with new values. Countries with long experiences in such systems plan a 'renovation' effort periodically (Kolbl 1987).

This paper attempts to describe a model of a multipurpose cadastral system where the implementation unites all the processes recommended by the National Research Council above in a uniform manner, using measurements as the basic data. However, a discussion of implementation details such as the required data structures is omitted to limit this paper to a reasonable length. It is also important that multipurpose cadastral systems literature separates the concepts involved in a computer program from the mechanics of their implementations.

The next section presents related work. It is followed by a discussion of the concepts and inherent problems of coordinate-based cadastral systems. A discussion about networks of control points as they apply to land surveying is then presented. The concepts and advantages of measurement-based cadastral systems are presented next, followed by a discussion of the architecture of such systems: the measurement database, the geometry module, and the user interface. Conclusions are given in the last section.

Related Work

The National Geodetic Survey (NGS) has completed the readjustment of the National Geodetic Reference System (NGRS) to the North American Datum of 1983 (NAD 83) (Schwarz 1989). Some geographic regions, however, are found to have a weak relative accuracy despite an overall improved NGRS for the nation. Ethridge (1989) described the use of a measurement database to upgrade the coordinates of the NGRS in regions where the relative accuracy is inadequate.

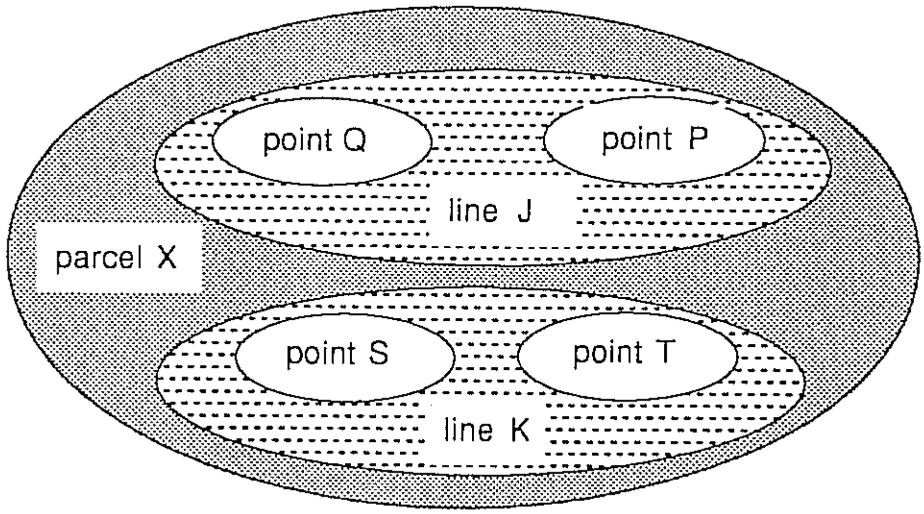
Jacobi (1988) discussed how discrepancies of coordinate values, after a revision or update of a digital map, can be eliminated if the original photogrammetric measurements of map points and geodetic measurements of control points are stored. In such an arrangement, new measurements are combined with old measurements and are simultaneously adjusted to obtain a unique set of coordinate values of map points whenever a map needs to be updated. This is in contrast with the normal practice of discarding the measurements after the coordinates of the associated points have been determined, which makes updating difficult (Figure 1).

Hintz et al. (1988), Hintz and Onsrud (1990) and Elfick (1989) described systems that manage surveying measurements. The primary aim of such systems is to effectively manage the huge amount of cadastral measurements inherent in any cadastral system. The described systems store cadastral measurements and periodically provide an updated set of parcel corner coordinate values by adjusting all related measurements. Storing raw cadastral measurements instead of coordinates, which are derived quantities, resulted in systems that are flexible, sensitive to changes, and that have the potential to be legally supportive (Moreno and Onsrud 1990; NSF 1985).

Although Ethridge's work was concerned with the NGRS upgrade, Jacobi's work was concerned with digital photogrammetric map revisions, and the works of Hintz and Elfick primarily support cadastral systems, they all have several characteristics in common: (1) measurements are second-class objects, (2) systems are basically measurement management systems to support coordinate-based systems, and (3) computed coordinate values are transmitted to the supported systems. These characteristics are shown in Figure 2.

Kjerne and Dueker (1988) argued that present approaches to cadastral system implementations do not capture the spatial relationships between cadastral objects as determined by surveyors. Only object locations in terms of coordinates are known while the knowledge of why the objects are there has been lost. They suggested that by modeling cadastral data using an object-oriented paradigm (Atkinson et al. 1989), cadastral systems are able to: (1) trace the chain of operations that leads to a particular object being at a particular place, and (2) update an object's location without having to undergo the coordinate reconstruction processes again. An object-oriented structure also allows flexibility in the order of entry of data in a cadastral system and thus permits revision and updating more easily. Figure 3 shows this object-oriented concept where, for example, parcel X and boundary line J know if point P has changed its position.

FIGURE 3.
Parcel X contains two boundary lines and each of the boundary lines contains two boundary points.



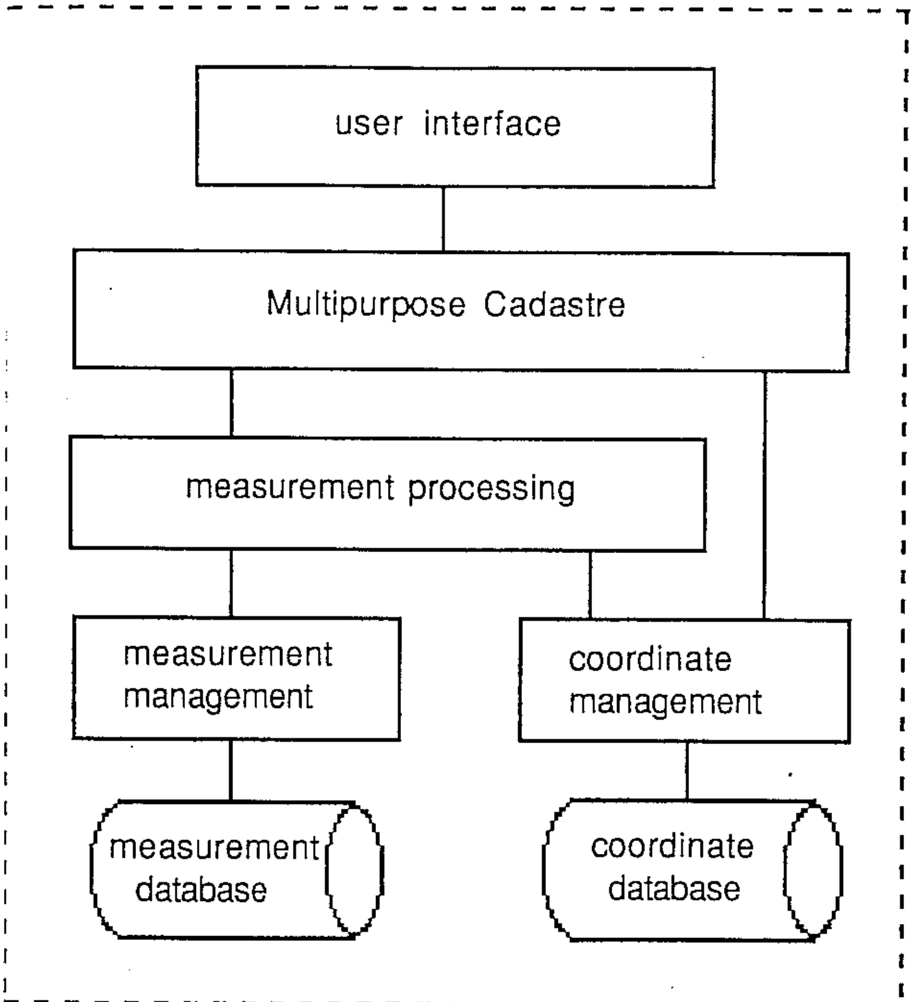
The work reported in this paper extends the works of Ethridge, Jacobi, Hintz, and Elfick, and integrates the work of Kjerne and Dueker. In doing so, the gap that separates the measurement management systems and the systems they support is removed; a measurement-based multipurpose cadastral system integrates a surveying measurement management system and a multipurpose cadastral system (Figure 4). However, it is not just an integration. In such a set-up (1) measurements are first-class objects; (2) measurements are the basic carrier of metric information; and (3) the measurement-management system plays a dominant role. Efficient management of measurements and related data requires a measurement database. A coordinate database facilitates operations where the use of coordinates is more appropriate. An appropriate user interface must also be integrated.

Coordinate-Based Systems

Geometric queries to a multipurpose cadastral system can be divided into topological and metric queries. Topological queries are concerned with the information that is invariant under topological transformations. Metric queries are those based on the notion of a distance. The question whether or not a house is inside a parcel is a topological question, while a question about the length of a boundary line is a metric one. Figure 5 illustrates the two types of queries.

The principal concept of a coordinate-based system is that the stored coordinate values are the primary sources of data providing answers to metric queries and possibly to topological queries as well. For example, if we query a coordinate-based system about the frontage of a parcel, the information is obtained by calculating the length of the

FIGURE 4.
The concepts of measurement-based multipurpose cadastral systems.



boundary line from the coordinate values of the end points.

An implementation of a coordinate-based multipurpose cadastral system starts with the establishment of a stable geodetic control network and the preparation of the base map. Later, measurements between parcel corners and other object points are adjusted to fit the control network. The adjusted coordinate values of parcel corners and other objects of interest are stored in the database. The coordinates from that time on serve as the basic and only carriers of metric information in the system, making the original measurements obsolete.

The implementation of a coordinate-based sytem is substantially different form the traditional method of surveying. In the past, the measurements were kept and carefully guarded (usually in the form of field books) after the maps or plans were drawn. The old measurements were usually consulted for related new work. For example, original measurements are utilized in the restoration of a lost boundary mark or in the subdivision of a land parcel. Unfortunately, the principle of guarding the old measurements is endangered by the advent of computerized cadastral systems. Today's multipurpose cadastral systems are built solely on coordinates with no linkages to measurements.

In many cases, parcel corners and other objects are digitized from old maps and plans because of speed and economy. The digitized coordinate values are then transformed to conform with the underlying coordinate system of the geodetic control network. In such situations, the actual measurements do not exist in the construction of the system and can never be consulted if the need should arise.

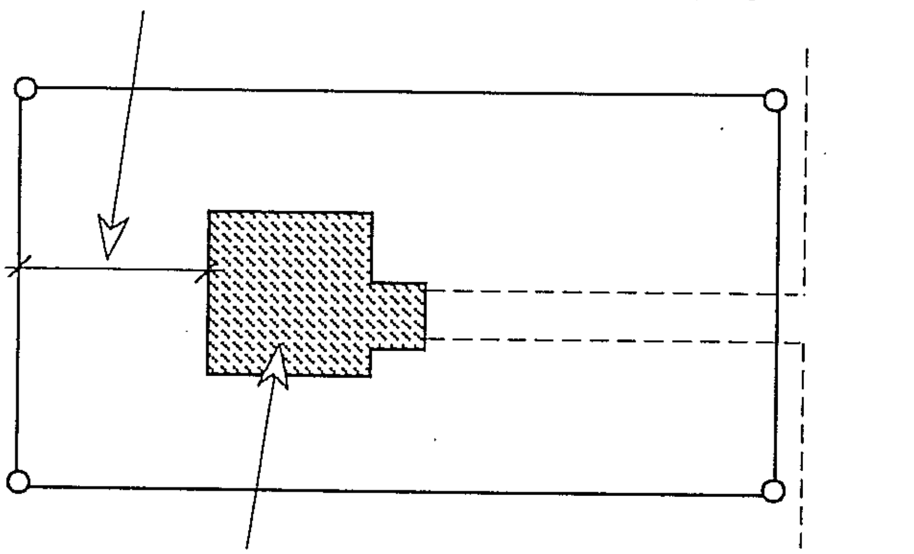
Coordinate-based multipurpose cadastral systems have several problems. The problems range from the time of initial conception and financing of the system to the actual implementation and maintenance. This multitude of problems has been described by several authors (Bauer 1982; Dale and McLaughlin 1988; Friedley 1989; Hebblethwaite 1989; Masters 1988; Scott 1987) and can be grouped into two general categories: implementation and maintenance.

Implementation

Creation of a good coverage of control points requires much effort and capital investment. These are the early obstacles to the implementation of a coordinate-based multipurpose cadastral system. Although satellite positioning techniques such as the Global Positioning System (GPS) have made this task more manageable, its cost is still beyond the limit that could easily be afforded by most local governments such as municipal and county administrations. Besides the cost of setting up the control points, the cost of converting cadastral and other related data into digital format to be stored in the database has to be considered, and experiences have shown that this cost is quite substantial (Parent, Joffe, and Finkle 1989; Thompson 1988).

Since a lot of expenses accrue at the time of system initiation, a coordinate-based system implementation demands a heavy investment at the beginning. There is also a long lead time from the moment of investment to the time the system can be used due to the sequential implementation procedure. Elected officials, with public demand to minimize taxes and expenditures, find it hard to make a large investment where the benefits may not be perceptible to the public for quite a few years. Because of the high front-end costs and small immediate return, elected officials (usually with short terms of office) tend to concentrate on other short-term issues and problems (Dueker 1987).

FIGURE 5.
Topological and metric queries.



Maintenance

The maintenance issues mostly revolve around updating the coordinate database and base map. The problems can be organized into four categories: (1) the integration of new measurements with existing coordinate values; (2) the integration of high-quality new measurements with low-quality coordinate values; (3) the continuously changing coordinate values of parcel corners; and (4) the evolving accuracy requirements of base maps.

Integration of new measurements with coordinate values: Integrating new measurements with stored coordinate values that were either computed from earlier measurements or digitized from other sources is an involved and expensive process. The correct method would be to obtain the earlier measurements and recalculate the coordinate values of all points after new measurements have been integrated. This method of updating a coordinate database is seldom used because of considerable efforts to recover the earlier measurements, if they are still available at all. The other option is to use a sequential adjustment technique. This method, however, requires the variances and covariances of the points from prior adjustments. Although storing the variances of point coordinate values may be justifiable, storing a huge amount of covariances is a forbidding task. To store the covariances of 10,000 points could require the storage of up to $(2\times10{,}000)^2$ values.

Integration of high-quality new measurements with low-quality coordinate values. Existing coordinate values in a system tend to be of lower quality than new measurements. The coordinate values are obtained either by digitizing from various maps and plans or computed from old measurements, which were acquired using less precise instruments and sometimes dubious procedures. Integrating new measurements acquired using today's high-technology instruments into existing coordinate sets poses a difficult problem. Most of the methods utilized do not take into consideration the quality of the existing coordinate values and the new measurements. As a result, there is a danger that precision is lost because new measurements are downgraded by fitting them into existing coordinate values. Discarding existing coordinates, on the other hand, may result in a loss of information.

Shifting effect of the cadastral layer: Layers of information in a multipurpose cadastral system are usually integrated through property corners. However, coordinate values of property corners in the cadastral layer are subject to constant updating due to, for example, new sub-division surveys, uncovered errors and blunders, and re-adjustment of the underlying geodetic reference framework (Hebblethwaite 1989). Since a coordinate-based system stores only coordinate values and discards the measurements that link the objects on the various layers, it loses the medium to propagate the changes of coordinate values in the cadastral layer to the other layers. As a result, it appears that the cadastral layer has moved when different layers of information are overlayed.

The adoption of a new datum (NAD 83) is an example of a process which causes the shifting effects (Bossler 1987). The problem arises after the new datum has been incorporated into the cadastral layer, for example, by readjusting measurements that are specific to this layer using the redefined control point coordinate values. While the parcel boundary points tied to geodetic control have been readjusted to the new datum, points in all other layers are still referenced to the old datum. The apparent shift of the cadastral layer with respect to the other layers when the overlay is done makes the information produced by such a system inconsistent (Figure 6).

Accuracy of base maps: The accuracy with which base maps are prepared depends on the use and value of the land. As the use of land changes over time, the quality of base maps may become insufficient making a re-survey to improve the accuracy necessary. Since it is generally impossible to accurately predict where development will occur, the recommended procedure is to measure the whole area according to a higher standard and prepare the base maps for higher accuracy than actually warranted. This practice of preparing base maps for possible future growth and needs that are still uncertain can be a waste of resources.

Control Points

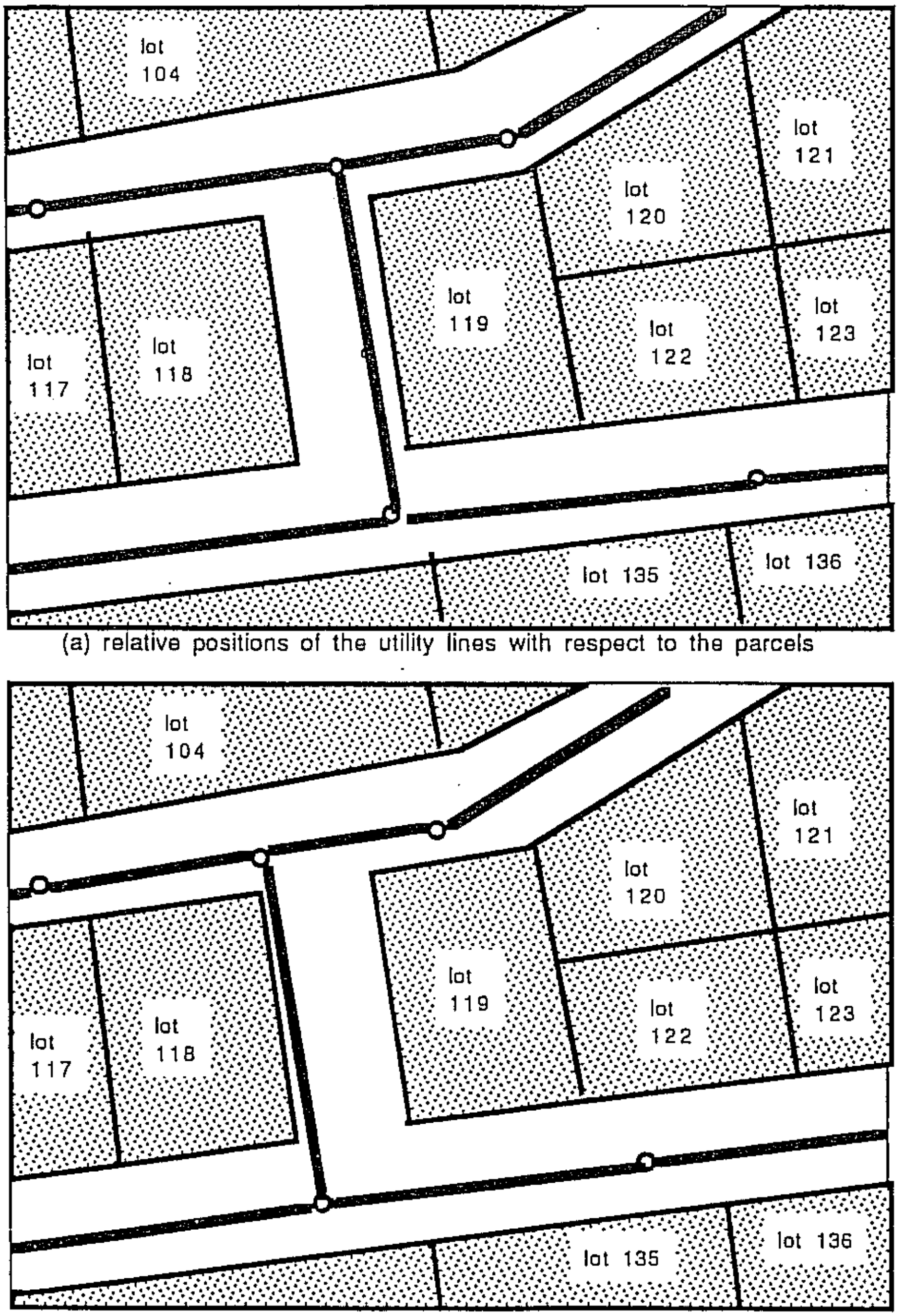
The majority of the problems inherent in present implementations of multipurpose cadastral systems is associated with the notions of networks of control points and hierarchical adjustments. Rethinking these notions opens up another view of position determinations and thus a new way of implementing a multipurpose cadastral system.

A network of control points is a set of points which may or may not be realized on the ground and whose coordinate values have been determined from a survey. The coordinate values of the control points are used as the basis for other dependent surveys. The surveys from which the control point coordinate values are obtained, known as control surveys, are usually of higher precision than the dependent surveys (NGS 1986).

The concept of control surveys and subsequent surveys is due to the classical methods of land surveying, primarily the hierarchical network adjustment perspective (Bomford 1975). Before the widespread use of computers, it was impossible to establish coordinate values of a set of points for an area of significant extension based on a single network adjustment. Surveyors lacked computational tools that enabled a large number of equations to be solved simultaneously. Even the methods employed in adjusting small networks attempted to reduce the number of equations to be solved by, for example, adopting the condition equation model (Bomford 1975).

The solution to the problem was to break up the task into smaller tasks using the principle of hierarchical network design. Consequently, this gave rise to different qualities of network points (characterized by the order of networks) with different levels of precision, and a heirarchy of adjustments where

FIGURE 6.
The cadastral layer appears to have been shifted with respect to the utility layer.



(a) relative positions of the utility lines with respect to the parcels

(b) the utility lines appear to have shifted after parcel corners have adopted a new set of coordinates

the coordinate values of the higher-quality network points govern the adjustment of the lower-quality network points. The coordinate values of the higher-quality points are usually held fixed (error free) in the adjustments to determine the coordinates of lower-quality points.

With the availability of digital computers and the speed of computing today, a greater number of equations can be solved at any single time. A larger number of measurements can be adjusted simultaneously and thus, for a lot of cases, fictitiously subdividing a network into a hierarchy is unnecessary.

Network points in dependent surveys should not be labelled as control points. The quality of network points should be determined purely from the precision of the coordinate values after the network measurements have been simultaneously adjusted; high-quality points are points with more precise coordinate values, i.e., small variances. To have high-quality points, precise measurements in sufficient density are needed as opposed to fallaciously dividing the points into different qualities dictated by the adjustment capability.

Measurement-based multipurpose cadastral systems will adhere to this approach. There is no reason to retain the old philosophy in an age where computing power is readily available. If partitioning of points is necessary, it should be done spatially (by regions), not hierarchically. Many advantages are expected from adopting this idea.

Concepts Of Measurement-Based Systems

The fundamental concept of measurement-based multipurpose cadastral systems is that measurements are the carriers of metric information (Buyong and Frank 1989). Consequently, updating a database of a measurement-based system with new measurement information only requires the addition of the measurements to the database. Users can directly communicate their original information to the system. Re-computation of coordinates is not imperative and can be deferred until needed by queries. The disseminated metric information is always up-to-date because the latest measurement can be integrated into the processing.

Implementation of a measurement-based system requires measurements to be stored in the database (Buyong and Frank 1989; Elfick 1989; Ethridge 1989; Frank and Studemann 1984; Hintz and Onsrud 1990; Jacobi 1988; Kjerne and Dueker 1988; Weitzman 1989) such that they become accessible for future use. These measurements include measurements between higher-quality points (in coordinate-based systems, such measurements are known as control point measurements), parcel boundary measurements, and measurements of other objects of interest.

Although measurements are the primary source of metric information, coordinate values are used where it is more appropriate. Graphical representation, spatial database access, and other tasks that do not need accurate and up-to-date information are examples where coordinates are useful. To satisfy the needs of these tasks, coordinate values are stored (Alonso et al. 1988). Thus, instead of re-computing the coordinate values each time a graphical representation of parcels is requested, the stored values are retrieved.

Periodic global processing of the measurements in the system is necessary to fulfill the need to have a reliable and consistent copy of coordinate values. This can be realized in several different ways. Two of the ways are: (1) to make the system process the measurements at certain pre-set time intervals; for example, at night when most computers are essentially idle, or (2) after a certain number of measurement changes have occurred.

Advantages Of Measurement-Based Systems

A measurement-based multipurpose cadastral system has several practical advantages over a coordinate-based implementation. The advantages lie primarily in the ease of updating, incremental implementation, systems as by-product of standard activities, improvement of accuracy over time, correct integration of different layers, preservation of background information as well as in several economic benefits.

Updating: The existence and the value of each measurement in a measurement-based system are independent of other measurements. This makes system updating easy. Integration of new measurements is done simply by adding the measurements into the database. Old and inaccurate measurements can coexist with better values or be deleted from the database without difficulty. The ease of updating also allows an organization to keep the data in a measurement-based system always current. Since answers to metric queries are processed only at the time they are needed, the latest available data can be incorporated. Thus, the information a measurement-based system provides is always up-to-date. It is anticipated that this advantage will become more significant as the functionality of a multipurpose cadastral system becomes more complex and the demand for accurate and up-to-date information increases.

Incremental implementation: The implementation of a measurement-based system can start with a small area of immediate concern such that a system with the necessary functionality can be set up rapidly. As time goes on and when money and manpower become available, neighboring areas can be incorporated by adding relevant measurements into the database. Islands that are initially developed independently can also be linked together.

System as a by-product of standard activities: Measurement-based systems do not demand special up-front data collection tasks. Existing measurements, however deficient, will form the basis of multipurpose cadastral systems and are supplemented by new measurements as they become available. The new measurements may come from standard daily operations of surveyors, like subdivision, refixation, and retracement surveys.

Improvement of accuracy: A measurement-based system can be set up with limited quality measurements. As expected, the accuracy of such a system is poor. However, the accuracy of the system improves as the system matures and more measurements are added. The improvement of accuracy can occur by special efforts, like the addition of GPS measurements, or from daily operations of surveyors. With the availability of more precise instruments to surveyors, cadastral measurements from standard activities certainly contribute to the improvement of the accuracy of the system. No extra overhead is required to support accuracy improvement since all procedures remain the same but are supported by a higher degree of automation and integration.

Integration of layers: In a measurement-based system, the measurements that determine the coordinate values of points in non-cadastral layers relative to property corners are kept in the system. Thus, the changes in the coordinate values of property corners in a cadastral layer, due to whatever reasons, are automatically propagated to other layers through these measurements. This is a special case of the integrated geometry concept (Frank and Kuhn 1986).

The adoption of a new geodetic datum for the cadastral layer in multipurpose cadastral systems, e.g., the current adoption of the NAD 83 datum to replace the NAD 27 datum, will produce no discrepancies in measurement-based systems. This is because coordinate values of points in all layers of information are computed from relevant measurements as they are needed. This ensures correct relative positions between points in the cadastral layer and points in other layers when the two layers are superimposed.

Preservation of background information: A measurement-based system retains the original measurements and their quality information (variances). Preserving the original data as opposed to the massaged data provides evidence for any information the system offers; users can determine the basis of answers to queries. The quality information about measurements in a system permits relative weights to be placed on them. It is foreseen that the availability of measurement variances will become one of the most important advantages as users become aware of the need to keep track of the quality of metric information (Chrisman 1984; Goodchild and Gopal 1989; Robinson and Frank 1985). A system with such capability affords a major step toward the goal of a legally supportive multipurpose cadastral system (Moreno and Onsrud 1990; NSF 1985).

Economic benefits: Among the economic benefits resulting from the technical advantages discussed above are the low start-up capital and the short lead-time from the moment of investment until a system can be used. First, the high cost of setting up a good coverage by a control network is avoided because its prior completion is unnecessary. A measurement-based system also avoids the up-front cost of converting data from the entire project area into digital format. The ability to implement the system in a gradual manner, starting with a small area of immediate concern, also makes large start-up capital unnecessary. Second, with a small area of initial implementation, a measurement-based system can be used as soon as it is set up. The benefits of having the system can be realized much faster and, most probably, the system can financially support itself for expansion if some kind of user fees are imposed. Thus, the small start-up cost, quick return on investment, and ability to quickly support itself make it more likely to gain support from the funding authority.

System Architecture

In the last two sections, the concepts of a measurement-based multipurpose cadastral system and several advantages it offers have been presented. The most important of all are the economic advantages which are no doubt the prime criteria for successful implementations. In this section, the architecture of a measurement-based system will be described. Because measurements are the primary data in a measurement-based system, the discussions of the design architecture are focused on them.

Measurement Database

Measurements are abstract relationships providing metric information about a set of points. Points can either be boundary points or survey points. Boundary points define the geometry of parcels, i.e., their location and extension. The location and extension of buildings, roads, rivers, utility lines, and like features are determined from the associated survey points.

The stored measurements can be categorized according to their sources: (1) terrestrial measurements, (2) GPS measurements, and (3) digitized data.

Terrestrial measurements: Terrestrial measurements encompass horizontal angles, horizontal distances, directions, bearings, and azimuths. These are the common forms of measurement found in surveying networks. While all types of measurements provide relative positions of points, azimuth and bearing measurements give one extra piece of information: they also provide the orientation of the network with respect to the adopted reference frame.

GPS measurements: This category of measurement is highly accurate and available only at selected points in a project area. Due to their inherent high accuracy, GPS measurements can be used to define the reference frame and to provide a homogeneous system of coordinates between isolated areas in a multipurpose cadastral system. Their high accuracy also makes them useful for curbing error propagation from other categories of measurements.

Digitized data: This is probably the cheapest type of (pseudo) measurements. Digitized data can be obtained from hard-copy maps and plans. They can be used to set up a system initially and can become the predominant category of measurements at the beginning, although this is not a requirement—a measurement-based system can be built without any digitized data. Other types of measurements can later gradually be introduced into the system. It should be kept in mind that digitized data must not be left alone to provide metric information as this would just create another coordinate-based system.

Points, lines, and polygons are other major objects in the database beside measurements. Each object has particular properties called attributes that describe it. Examples of some of the prominent attributes of the objects are:

1) *Measurements*—observed values, variance, observer and date observed
2) *Points*—point number, coordinates, coordinate variances and point types
3) *Lines*—lines types
4) *Polygons*—polygon types and area

Geometry Module

In order for the measurement-based system to have a usable representation of the geometric properties of the real world, measurements must be processed before any metric information is disseminated. Measurement processing combines available measurements, detects blunders in the measurements, and imposes additional geometric constraints if necessary. The most suitable measurement processing method is the technique of least squares adjustment (Mikhail 1976).

The method of least squares allows all categories of measurements, each with different accuracy, to be processed in an integrated way. Measurements can be independently weighted and the inverse of the measurement variance, expressed in some standard unit, is a natural choice for the weight. The contribution of each measurement to the coordinate values is thus determined by its variance. Since measurements with small variances will have large weights, their contribution to the adjusted coordinate values is more significant than the contribution of measurements with large variances. These are desired properties for integrating lower-accuracy terrestrial, cadastral or digitized coordinate measurements with higher-accuracy GPS measurements to obtain an optimal solution. The method of least squares also permits easy integration of nonmeasured data, known as *a priori* information, in the measurement processing.

A pre-processing module is required for each measurement type due to the availability of a mixture of categories of measurements and a number of parameters on which each measurement category is dependent. With the pre-processing, each measurement type is prepared for input into the least squares adjustment module in a uniform manner. Much of the unwanted or nuisance parameters and systematic effects are eliminated during measurement pre-processing.

Blunders of various kinds may be present in the measurements stored in a system. A system will lose its trustworthiness if the information it produces contains excessive blunders. A blunder-detection algorithm based on a sound statistical foundation can be integrated into the adjustment module. This way, blunders of significant magnitude are detectable prior to the information being given out. Procedures for post-adjustment blunder detection are discussed by Baarda (1967) and Pope (1976). These methods of blunder detection can be employed immediately after an adjustment has been carried out. A technique to detect blunders before an adjustment, introduced by Vonderohe and Hintz (1987), can be used during the measurement preprocessing stage.

Geometric constraints can be incorporated into the adjustment to improve the accuracy of information furnished. Simple examples of geometric constraints are perpendicularity, colinearity, and parallelism. These constraints are useful in areas where the quality of the available measurements is insufficient to accurately determine the desired geometry; for example, when only digitized coordinates are available, the low quality of digitized coordinate values makes additional constraints a valuable supplement. There is no difference between a measurement and constraint from the data modeling perspective; for example, it does not make any difference whether a distance is measured 10 meters or it is constrained to be 10 meters (Kuhn 1990). Hesse, Benwell, and Williamson (1990) discussed the application of geometric constraints to digitized cadastral data in a multipurpose cadastral system.

For practical reasons, not all the measurements in a database are adjusted whenever coordinate values of some points are needed to answer queries. Only measurements around the neighborhood of the queried area that significantly influence the desired results need to be processed. This is due to the localized nature of surveying information propagation (Halmos, Kadar, and Karsay 1974). Judging from experiments carried out using simulated terrestrial data, it is only necessary to include measurements up to four measurements away around an area of interest. Inclusion of more distant measurements does not significantly improve the adjusted coordinate values of the queried area points (Buyong and Kuhn 1990).

As mentioned before, the geometry module is a tool to obtain usable metric representation from measurements. This tool, as a complete package, may be unavailable on the market. Since the theories, however, are relatively well understood, creating the package is not seen as a major task. Several good surveying network adjustment programs with blunder detection and additional constraint capabilities such as OPTUN (Grundig and Bahndorf 1984), CANDSN (Mepham and Krakiwsky 1984), and STAR*NET (Curry and Sawyer 1989) are already available on the market. A geometry module can be built around any of these programs.

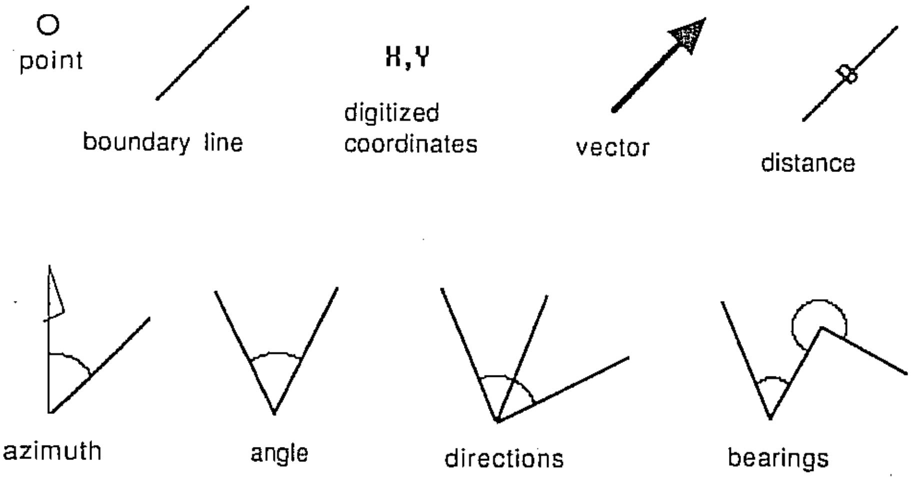
User Interface

Direct manipulation interaction has been generally accepted to be an effective form of human-computer interaction as evidenced by its use in Macintosh computers, Microsoft Windows on IBM-PC micro-computers, and Unix operating systems. It is especially suitable for treating spatial objects because it takes advantage of the spatial properties inherent in such objects. The user interface for measurement-based multipurpose cadastral systems should adopt the direct manipulation concept.

The user interface for measurement-based systems should support objects that are meaningful to the users, i.e., the different types of measurements (such as angles, distance and directions); points (such as boundary and survey points); lines (such as boundary and survey lines); and polygonal objects (such as parcels and buildings). A set of operations to manipulate the objects must be provided; input, edit and delete operations are needed for storing, modifying and removing objects in the database, and a find operation is needed for searching objects in the database when at least one of their attribute values is known.

The most important requirement for the direct manip-

FIGURE 7.
Graphical representations of the different types of measurements.



ulation user interface is the visualization of the objects to be manipulated (Shneiderman 1987). Without the different objects being displayed on the screen, direct manipulation is not possible. Figure 7 shows possible representations of the different types of measurements.

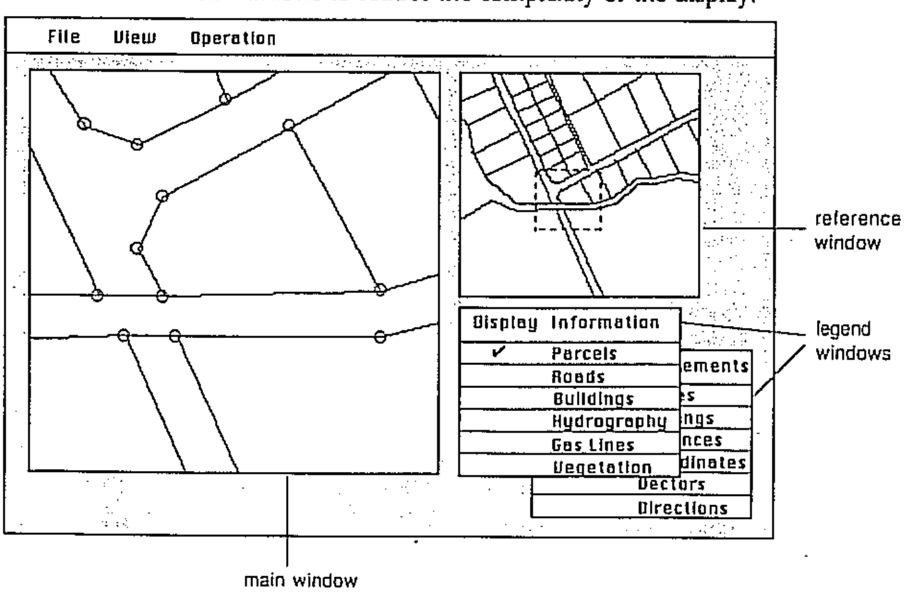
The operations of the user interface can be represented as menu items, organized in the form of pull-down menus. They are grouped according to their semantics relevant to the user's tasks. For example, operations directly relevant to the cadastral objects such as input, edit, and delete are grouped together and are separated from operations that are concerned with the display.

A display that shows all the objects in an area is not conducive to effective human-computer interaction because of the limited size of the computer screen and the existence of an upper bound of human perception of the complexity of graphical representations. Given a typical area of a multipurpose cadastre that may be in the order of several thousand square kilometers, and the availability of several different types of objects which sometimes are clustered to a few selected places, a way to reduce the complexity of a display must be provided.

The reduction in the display complexity can be achieved through effective use of multiple windows (Herot 1982; Jackson 1990). A small reference window is used to display an overview of the entire scene and a bigger main window is used to display a portion of the selected scene at a larger scale. Two legend windows permit the user to select only certain types of objects to be displayed; one legend window deals specifically with the different types of measurements while the other window deals with the rest of the objects. Figure 8 shows the different windows of the user interface with only parcels being displayed in the main window.

Interfaces to transfer measurement data from data collecting systems such as automatic field data collectors, photogrammetric triangulation systems, and GPS receivers must also be provided. Such interfaces provide convenient and

FIGURE 8.
The use of different windows to reduce the complexity of the display.



easy input of measurements that originate from these measuring systems. Editing of these measurements can be performed in the same way after they have been stored in the system.

Conclusion

A measurement-based multipurpose cadastral system uses measurement data as the basic carrier of metric information. This concept is realized by allowing the processing of the measurements to be suspended until information is needed.

A measurement database, a geometry module, and a user interface are the three major components of the architecture of a measurement-based system. The geometry module contains measurements pre-processing, processing, and blunder detection algorithms. An efficient management of the measurements is furnished by the measurement database. A user interface that presents objects that are meaningful to users in a very simple fashion is indispensable for the system.

The advantages of a measurement-based system over a coordinate-based system are significant. An implementation does not require prior completion of a network of control points. Initially, a measurement-based system can be implemented within a small area of immediate concern and expanded at a later stage when needs and resources warrant it. Thus, it requires a low start-up capital and provides faster returns on the investment. New measurements can be integrated easily and the overall precision of a system improved over time, as more or better measurements are added. Changes in the position of parcel corners are automatically propagated to other non-cadastral layers through the stored measurements. The background information which determined the location of parcel corners and their accuracies is also retained in the system.

The evolutionary and incremental approach to building a measurement-based multipurpose cadastral system is especially attractive. Its implementation strategy is suitable for local governments such as municipalities and counties. These are the organizations that really need a multipurpose cadastral system, but lacked the funds to pursue the idea; the implementations of coordinate-based systems require substantial preparatory tasks to be completed before the system could be used.

Acknowledgements

The authors would like to thank the National Geodetic Survey for financial support of this project. Additional support for related work that was beneficial to this topic came from the National Science Foundation under grants No. SES-8810917. The authors are also grateful to Lothar Grundig, Karsten Jacobsen and Raymond Hintz for many fruitful discussions.

References

Alonso, R., D. Barbara, H. Garcia-Molina, and S. Abad. 1988. "Quasi-Copies: Efficient Data Sharing for Information Retrieval Systems." In *Advances in Database Technology-EDBT '88*. Ed. by J.W. Schmidt, S. Ceri and M. Missikof, pp. 443–468. New York: Springer Verlag.

Atkinson, M., D. DeWitt, D. Maier, F.B. Altair, K. Dittrich, and S. Zdonik. 1989. "The Object-Oriented Database System Manifesto." *Proceedings of the Deductive and Object-Oriented Database Conference*, Kyoto, Japan, pp. 40–57.

Baarda, W. 1967. "Statistical Concepts in Geodesy." *Publications on Geodesy New Series 2(4)*. Netherlands Geodetic Commission, Delft, The Netherlands.

Bauer, K.W. 1982. "Problems of Political Support at the Local Level for the Development of Technically Sophisticated Land Information Systems." *Proceedings of the International Symposium on Land Information at the Local Level*, Orono, Maine, Aug 9–12, pp. 13–24.

Bomford, G. 1975. *Geodesy*. Oxford: Clarendon.

Boosler, J.D. 1987. "Geographical Information Systems and NAD 83." *Proceedings of the International Geographic Information Systems (IGIS) Symposium*, Arlington, Virginia, Nov 15–18, Vol. 2, pp. 297–304.

Buyong, T.B., and A.U. Frank. 1989. "Measurement-Based Multipurpose Cadastre." *Proceedings of the ACSM/ASPRS Annual Convention*, Baltimore, Maryland, Apr 2–7, Vol. 5, pp. 58–66.

Buyong, T.B., and W. Kuhn. 1990. "Local Adjustment for Cadastral Measurement Databases." *Proceedings of the ACSM/ASPRS Annual Convention*, Denver, Colorado, March 18–23, Vol. 3, pp. 19–27.

Chrisman, N. 1984. "The Role of Quality Information in the Long-Term Functioning of a Geographic Information System." *Proceedings of the 6th International Symposium on Computer Assisted Cartography*, Washington D.C., pp. 303–312.

Curry, S., and R. Sawyer. 1989. "STAR*NET: Rigorous 2D and 3D Network Adjustment Program." *Proceedings of the ACSM/ASPRS Annual Convention*, Baltimore, Maryland, April 2–7, Vol. 5, pp. 269–277.

Dale, P.F., and J.D. McLaughlin. 1988. *Land Information Management*. New York: Oxford University Press.

Dueker, K.J. 1987. "Multi-Purpose Land Information Systems: Technical, Economic and Institutional Issues." *Proceedings of the 8th International Symposium on Computer-Assisted Cartography*, Baltimore, Maryland, Mar 29–Apr 3, pp. 1–11.

Elfick, M.H. 1989. "Management of Land Boundary Information." *Proceedings of the 31st Australian Survey Congress*, Hobart, Australia, pp. 103–113.

Ethridge, M.M. 1989. "Does the National Geodetic Reference System Need to be Upgraded?" *Point of Beginning*, October/November, pp. 26–34.

Frank, A.U., and W. Kuhn. 1986. "Cell Graphs: A Provable Correct Method for The Storage of Geometry." *Proceedings of the 2nd International Symposium on Spatial Data Handling*, Seattle, Washington, Jul 5–10, pp. 411–436.

Frank, A.U., and B. Studemann. 1984. "Datenstruktur von Messdaten." Paper presented at the International Course for Engineering Surveys, Graz, Austria.

Friedley, D. 1989. "Digital Cadastral Mapping Maintenance Issues in Local Government LIS/GIS Programs." Paper presented at the URISA Annual Conference, Boston, Massachusetts, Aug 6–10.
Goodchild, M.F., and S. Gopal Ed. 1989. *The Accuracy of Spatial Databases.* New York: Taylor & Francis.
Grundig, L., and J. Bahndorf. 1984. "Accuracy and Reliability in Geodetic Networks—Program System OPTUN." *Journal of Surveying Engineering,* Vol. 110, no. 2, pp. 133–145.
Halmos, F., I. Kadar, and F. Karsay. 1974. "Local Adjustment by Least Squares Filtering." *Bulletin Geodesique,* no. 111, pp. 21–51.
Hebblethwaite, D.H. 1989. "Concepts for Coping with a Shifting Cadastral Model." *The Australian Surveyor,* Vol. 34, no. 5, pp. 486–493.
Herot, C.F. 1982. "Graphical User Interfaces." *In Human Factors and Interactive Computer Systems.* Edited by Y. Vassiliou, pp. 83–103. Norwood: Alex.
Hesse, W., G.L. Benwell, and I.P. Williamson. 1990. "Optimizing, Maintaining and Updating the Spatial Accuracy of Digital Cadastral Databases." *The Australian Surveyor,* Vol. 35, no. 2, pp. 109–119.
Hintz, R.J., W.J. Blackham, B.M. Dana, and J.M. Kang. 1988. "Least Squares Analysis in Temporal Coordinate and Measurement Management." *Surveying and Mapping,* Vol. 48, no. 3, pp. 173–183.
Hintz, R.J., and H.J. Onsrud. 1990. "Upgrading Real Property Boundary Information in a GIS." *URISA Journal,* Vol. 2, no. 1, pp. 2–10.
Jackson, J.P. 1990. "Developing an Effective Human Interface for Geographical Information Systems Using Metaphors." *Proceedings of the ACSM/ASPRS Annual Conference,* Denver, Colorado, Mar 18–23, Vol. 3, pp. 117–125.
Jacobi, Ole. 1988. "Error Propagation in Digital Maps." *Proceedings of the XVI Congress of International Society for Photogrammetry and Remote Sensing,* Kyoto, Japan, Jul 1–10, Vol. 3, pp. 348–356.
Kjerne, D., and K.J. Dueker. 1988. "Modelling Cadastral Spatial Relationship Using Smalltalk-80." *Proceedings of the GIS/LIS '88 Conference,* San Antonio, Texas, Nov 30–Dec 2, Vol. 1, pp. 373–385.
Kolbl, O. (Ed.) 1987. "Proceedings of the Workshop on Cadastral Renovation." Ecole Polytechnique Federale, Lausanne, Switzerland.
Kuhn, W. 1990. "From Constructing Towards Editing Geometry." *Proceedings of the ACSM/ASPRS Annual Convention,* Denver, Colorado, Mar 18–23, Vol. 1, pp. 153–164.
Masters, E.G. 1988. "Upgrading A Digital Graphic Database." *Proceedings of the URPIS 16,* Sydney, Australia, pp. 384–391.
Mepham, M.P., and E.J. Krakiwsky. 1984. "CANDSN: Computer Aided Network Design and Adjustment System." *The Canadian Surveyor,* Vol. 38, no. 2, pp. 99–114.
Mikhail, E.M. 1976. *Observations and Least Squares.* New York: Dun-Donnely.
Moreno, R.J., and H.J. Onsrud 1990. "Legally Supportable Cadastral Information System." *Proceedings of the ACSM/ASPRS Annual Convention,* Denver, Colorado, Mar 18–23, Vol. 1, pp. 275–279.
National Geodetic Survey. 1986. *Geodetic Glossary.* Rockville, Maryland: Department of Commerce.
National Research Council 1980. *Needs for a Multipurpose Cadastre.* Washington DC: National Academy Press.
National Research Council 1983. *Procedures and Standards for a Multipurpose Cadastre.* Washington DC: National Academy Press.
National Science Foundation. 1985. "Report of The Workshop on Fundamental Research Needs in Surveying, Mapping, and Land Information Systems." Virginia Polytechnic Institute and State University, Blacksburg, Virginia.
Parent, P., B. Joffe, and R. Finkle. 1989. "Estimating the Cost of Building Your AM/GIS Database." *Proceedings of the GIS/LIS '89,* Orlando Florida, Nov 26–30, Vol. 1, pp. 143-151.
Pope, A.J. 1976. "The Statistics of Residuals and the Detection of Outliners." *NOAA Technical Report NOS 65, NGS 1.* Department of Commerce, Rockville, Maryland.
Robinson, V.B., and A.U. Frank. 1985. "About Different Kinds of Uncertainty in Collections of Spatial Data." *Proceedings of the 7th International Symposium on Computer Assisted Cartography,* Washington DC, Mar 11–14, PP. 440–449.
Schwarz, C.R. 1989. *North American Datum of 1983.* Rockville Maryland: National Geodetic Survey.
Scott, C.M. 1987. "Land Base Maintenance." *Proceedings of the AM/FM International Conference X,* Snowmass, Colorado, Jul 20–23, pp. 299–302.
Shneiderman, B. 1987. *Designing the User Interface: Strategies for Effective Human-Computer Interaction.* New York: Addison-Wesley.
Thompson, R.W. 1988. "The Reality of Data Conversion." *Proceedings of the AM/FM International Educational Conference XI,* Snowmass, Colorado, Jul 18-21, pp. 664–671.
Vonderohe, A.P. and R.J. Hintz. 1987. "Automated a priori Blunder Detection in Horizontal Control Networks." *Surveying and Mapping,* Vol. 47, no. 4, pp. 259–268.
Weitzmann, E. 1989. "Measurement Database for Property Mapping." Paper Presented at the URISA Annual Conference, Boston, Massachusetts, Aug 6–10.
Wentworth, M.J. 1989. "Implementation of a GIS Project in a Local Government Environment: The Long and Winding Road." *Proceedings of the URISA Annual Conference,* Boston, Massachusetts, Aug 6–10, Vol. 2, pp. 198–209.