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SYNTHESIS 301

NATIONAL
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PROGRAM

Collecting, Processing, and Integrating GPS Data into GIS

A Synthesis of Highway Practice

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A Synthesis of Highway Practice

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SUBJECT AREAS
Planning and Administration and Highway Operations, Capacity, and Traffic Control

Research Sponsored by the American Association of State Highway and Transportation Officials
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TRANSPORTATION RESEARCH BOARD — NATIONAL RESEARCH COUNCIL

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communication and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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NOTICE

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration of the U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis report will be of interest to various transportation-related groups around the world involved in collecting positional data with global positioning systems (GPS) and integrating these data into existing geographic information systems (GIS). The focus is on the major issues that these groups are facing with data collection, data smoothing, and data integration, including identification of inaccurate, bad, or missing data points, and the lack of standard map matching algorithms. It addresses the fact that each application uses its own GPS equipment, GIS database, and internal set of GPS data processing rules, and that information sharing and coordination has been limited. This synthesis was accomplished through a literature review and a survey of the state-of-the-practice activities in GPS data collection, data smoothing, and map matching.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

This report of the Transportation Research Board provides information on the potential and the problems of integrating GPS data with data from GIS to provide departments of transportation with a powerful set of planning and programming tools. It addresses existing data standards and their applicability, procedures for processing and integrating spatial data, map matching algorithms and protocols, and recent developments in positioning, including cellular technology. The synthesis identifies a six-step method designed to help improve the quality of maps and reduce the severity of problems associated with GPS–GIS integration.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the available information was assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the author's research in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

CONTENTS

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This study was managed by Stephen F. Maher, P.E., Manager, Synthesis Studies who worked with the consultant, the Topic Panel, and the Project 20-5 Committee in the development and review of the report. Assistance in project scope development was provided by Donna L. Vlasak, Senior Program Officer. Don Tippman was responsible for editing and production. Cheryl Keith assisted in meeting logistics and distribution of the questionnaire and draft reports.

Crawford F. Jencks, Manager, National Cooperative Highway Research Program, assisted the NCHRP 20-5 Committee and the Synthesis staff.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance are appreciated.

COLLECTING, PROCESSING, AND INTEGRATING GPS DATA INTO GIS

SUMMARY

The integration of global positioning system (GPS) data with data from a geographic information system (GIS) is beginning to provide departments of transportation (DOTs) and metropolitan planning organizations (MPOs) with a powerful set of planning and programming tools. At the same time, integrating data from these two technologies creates new problems for the same agencies. The central problem associated with merging GPS points with a GIS base map is identified as the "map matching" problem.

The focus of the synthesis is on the major issues associated with GPS and GIS data integration and how to address them for digital mapping applications related to transportation. The synthesis, through the use of transportation, GIS, and GPS literature, identifies the problems that integration creates. In addition, this synthesis discusses ways that the problems can be addressed. Examples of how different researchers and agencies have resolved the problems are summarized throughout the document.

Transportation agencies, including DOTs, MPOs, and private firms were mailed a questionnaire in May 2000, to identify how they address problems associated with GPS–GIS data integration. The results of the survey represent the views of 47 respondents, and their comments are interspersed throughout the synthesis. The survey results also identify standards used by agencies to minimize or eliminate the integration problem and specific problems the agencies face when attempting to resolve the map matching issue. Agency responses to the survey also provide information about the characteristics of those maps made by them.

The synthesis identifies a six-step method that can help to improve the quality of maps and reduce the severity of problems associated with GPS–GIS integration. Mobile GPS is mentioned as a primary set of tools and techniques designed to obtain accurate GPS points for integration purposes. Wireless communication technology is also discussed as a supplement or perhaps in some applications as a replacement for GPS data. The results from the synthesis survey of DOTs indicate that this option lies in the future.

It is clear that GPS and GIS have become important tools to DOTs and MPOs. Learning how to effectively and efficiently integrate the two technologies can only increase their usefulness and value to transportation agencies.

CHAPTER ONE

INTRODUCTION

BACKGROUND

State departments of transportation (DOTs) and metropolitan planning organizations (MPOs) use geographic information systems (GIS) as a basic tool for displaying maps and for data analysis. The addition of global positioning system (GPS) tools to mapping applications helps provide more accurate position data and reduces the cost of data collection. The combination of digital mapping with an underlying digital spatial database, a GIS, provides a range of flexibility in mapping and spatial analysis capabilities that, until recently, has been rare in transportation agencies.

The integration of the two technologies gives capabilities to DOTs and MPOs that did not exist 10 years ago. For example, tracking a vehicle on a roadway in real time by collecting GPS points and then observing the vehicle within a GIS can be useful for fleet management or to determine average vehicle speed.

GPS data collection is used for a wide variety of applications. The most common use by the agencies responding to the synthesis questionnaire is locating new roads and entering them into the agency's GIS. Other uses include locating intersections, call boxes, and mile markers; photolog control; and wetlands delineation. Surveying was also identified as a common use of GPS tools. DOT surveyors use GPS for control surveys, vertical and horizontal control, topography, and photogrammetric control.

GIS AND GPS IN TRANSPORTATION AGENCIES

In a little more than 35 years, GIS has revolutionized mapping. The first acknowledged GIS was the Canadian Geographic Information System created in 1964 for the Agricultural Rehabilitation and Development Agency Program (*1*). Early systems in the United States included the New York State Land Use and Natural Resources Information System created in 1967 and the Minnesota Land Management Information System developed in 1969 (*2*). Since the creation of these pioneer systems, the number of users of GIS has risen from hundreds to thousands of trained professionals in a wide variety of fields.

GIS for transportation has been used in state DOTs for more than 15 years. One of the earliest users of digital spatial data was the Wisconsin DOT, who initially used GIS for transportation for mapping highway mile markers (personal communication, David Fletcher, November 15, 2000).

Generally, GPS has been available to the public since 1985 (*3*). The more experienced DOTs have used GPS for 14 years, with the median number of years of being 7. Ten DOTs reported having less than 1 year of experience with GPS.

SURVEYING AND MAPPING IN TRANSPORTATION AGENCIES

The accuracy levels of GPS and GIS required by state DOTs can be divided into two general categories—surveying and mapping. Surveying means locating and identifying points on a map that correspond to features on the ground with an accuracy of less than 0.5 m and often at 2 cm or less. Mapping means placing features on a map, identifying them, and accepting accuracy levels anywhere from 1 m up to 30 m or more. Surveys are generally used by transportation engineers and surveyors, whereas planners and GIS analysts primarily use mapping. Examples of high accuracy applications include right-of-way determination, road alignment, and property boundary delineation. Mapping applications include video logging, milepost indicators, wetlands delineation, or highway corridor specification.

PROBLEM STATEMENT

Using GIS and GPS for mapping in DOTs has increased accuracy, decreased costs, reduced project completion time, and improved overall map quality (*3*). At the same time, the integration of GIS and GPS has created new problems, including identification of inaccurate and bad data points, missing data points, and the lack of standard map matching algorithms, that must be overcome if the full benefit of the two technologies is to be obtained.

The most serious integration problem is spatial mismatch or map matching. The central question for the synthesis is, how do we overcome the spatial mismatch problem and make GPS and GIS work together to provide DOTs and MPOs more powerful tools for analysis? Spatial mismatch can be defined as the lack of congruency between a feature on the earth's surface as specified by a

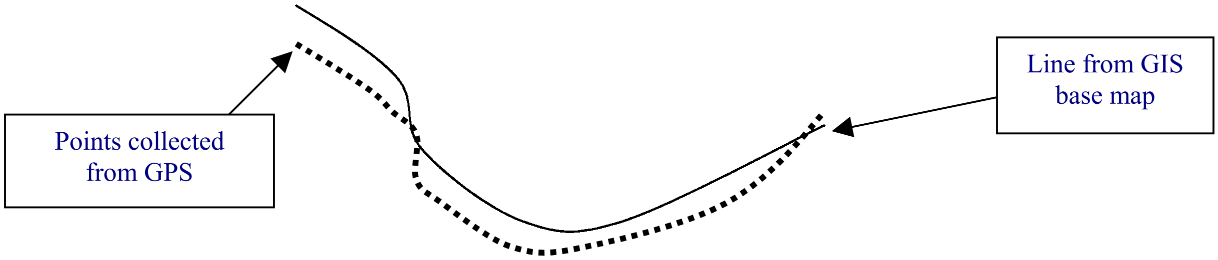

FIGURE 1 Map matching—A graphic definition.

FIGURE 2 Typical map matching problem [source: Wolf (*7*)].

GPS point and the location of the same feature within a digital base map. In other words, the two features do not line up (Figures 1 and 2). This can occur because of poor GPS data collection procedures, limits to the basic accuracy of the GPS unit, limits to the accuracy of the GIS source data, a flawed GIS digital base map, or some combination thereof (*4*). Two other reasons for spatial mismatch are the use of different map projections and different accuracy specifications.

The map matching problem has been observed in a variety of applications including

- Travel surveys—Locating travel routes within a digital base map when provided with a route generated from in-vehicle GPS collected points and identifying points that are trip origins and destinations.
- Speed studies—Comparing GPS locations along a specified route to predetermined intersection locations on a digital map to calculate travel speed.
- Fleet management—Identifying the location of a vehicle on a road network.
- Roadway inventory—Comparing the alignment of a roadway on an existing 1:24,000 scale digital map and the alignment as shown by GPS points collected at an accuracy of 1 m.
- Incident locations—Locations of accidents as identified by GPS points and the need to dynamically segment a road network associated with a given location.

SCOPE OF THE SYNTHESIS

The objective of the synthesis is to specify the major issues associated with the combined use of GPS and GIS and how to address them for digital mapping applications related to transportation. In chapters 3 and 4, many of the responses to the synthesis questionnaire indicate survey grade accuracy levels and surveying applications. However, the use of GIS in the context of data collected for surveying purposes (submeter) is generally beyond the scope of the synthesis.

Method

There were two main sources of information for the synthesis. The first was the GPS and GIS literature. Also, transportation application literature that integrated GPS and GIS was reviewed. The primary sources of this information were research reports from the TRB and NCHRP, MPO reports, consultant reports, and related transportation publications. In addition, case studies were drawn from trade journals that present recent experiences in the combined application of GPS and GIS.

The second source of information regarding GPS–GIS integration was the collective experience of DOTs, MPOs, and consultants. To identify this information, a survey questionnaire was sent to all DOTs and a small set of selected MPOs. A total of 27 DOTs responded to the survey. Duplicate responses from different departments within the same DOTs brought the total number of DOT responses to 36. In addition, six MPOs responded to the questionnaire, as did one private consulting firm. Follow-up interviews were held with a small number of agency staff who were identified as knowledgeable about the synthesis topic. Survey responses are summarized and presented in the appropriate sections throughout chapters 2, 3, 4, and 5. For ease of analysis, the different types of agencies are not specified in the results reported.

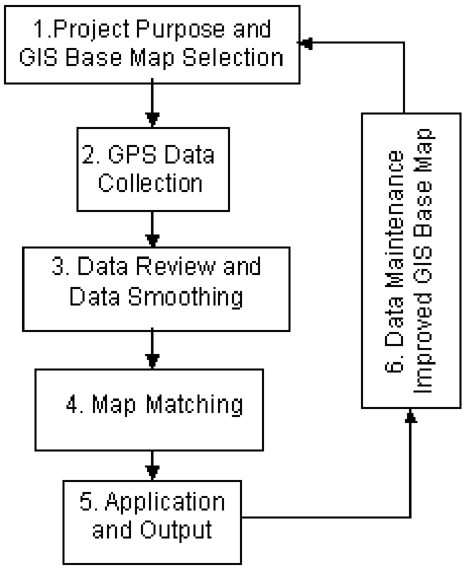

FIGURE 3 GPS–GIS integration process.

Synthesis Organization

The GPS–GIS integration process includes the following six steps (Figure 3):

1. Project purpose and GIS base map selection,
2. GPS data collection,
3. Data review and smoothing,
4. Map matching,
5. Application and output, and
6. Data maintenance and improving the GIS base map.

Project purpose and GIS base map selection (step 1) are discussed in chapter 2. The importance of specifying the project purpose before beginning the project is emphasized. It is suggested that there is need for an accurate and current GIS base map at the beginning of a project. GPS data collection (step 2) is presented in chapter 3. It focuses on the use of mobile GPS and the problems associated with this type of GPS data collection. The chapter is based on

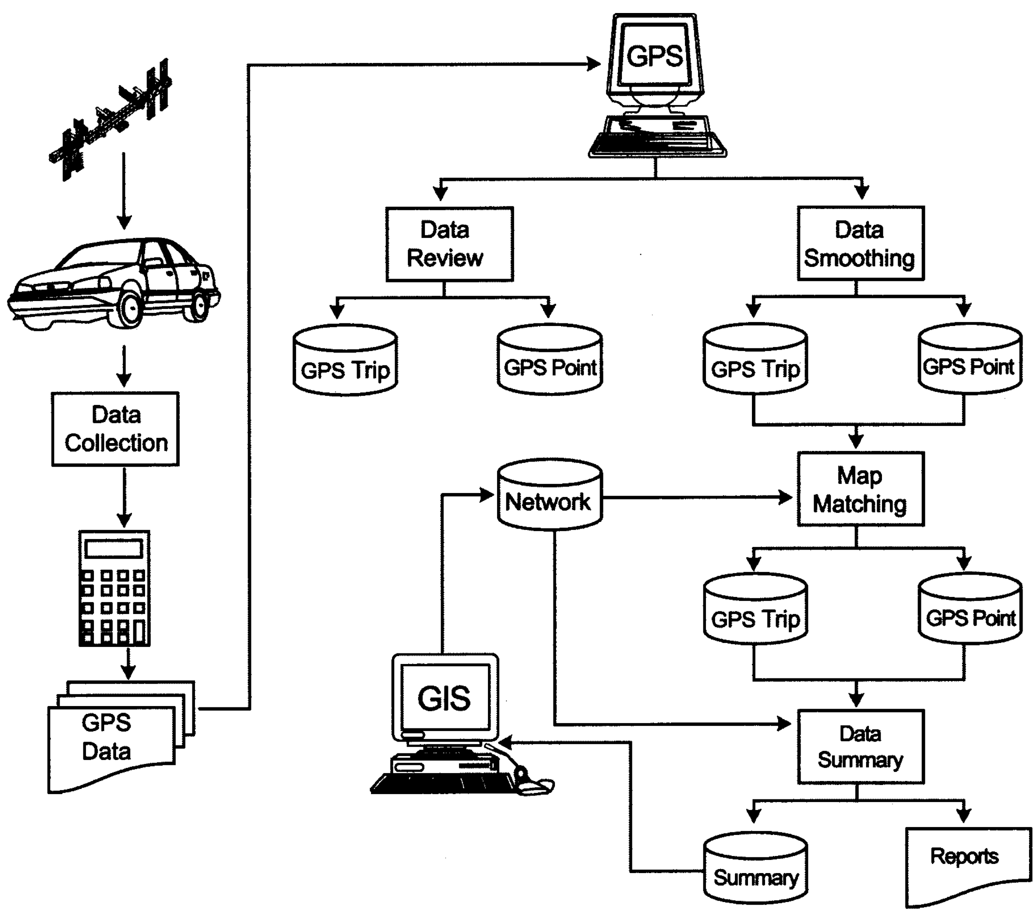

FIGURE 4 Roden software manual outline and GPS–GIS integration scheme.

research efforts that have employed GPS data in travel surveys and related projects. In addition, a series of standard GPS data collection concerns are also presented. Data review and smoothing (step 3), adjustments to GPS and GIS data, are discussed in chapter 4. This is done to ensure that data used for analysis purposes are complete and accurate. Chapter 5 reviews the techniques associated with map matching (step 4). This chapter also discusses the concept of map matching techniques used to line up GPS and GIS data. Application and output (step 5) are also briefly mentioned in this chapter, along with data maintenance and improving the GIS base map (step 6).

Chapter 6 reviews methods and potential uses of wireless technology and dead reckoning (inertial navigation) to supplement or replace GPS positioning data. It discusses alternative mechanisms for collecting *x* and *y* positions and the implications they might have for automated vehicle location, travel surveys, and other applications. Chapter 7 (Conclusions) discusses the major points from the synthesis.

There are a series of additional explanatory sections at the end of the synthesis. The Glossary provides further information on technical terms that are frequently used in the synthesis. Appendix A reproduces the questionnaire used to gather survey responses from DOTs and MPOs. Appendix B is a tabular listing of the survey results. Appendix C presents the Table of Contents to the Oregon DOT GPS Standards Manual. Appendix D contains the Tennessee DOT standards for metadata. Appendix E identifies a set of procedures that can be used to integrate GPS and GIS, which are based on the information gathered for the synthesis. Finally, Appendix F is a list of Internet sites that provide more information on GPS data collection, GIS, and the integration of the two.

CONCEPTUAL ORGANIZATION OF THE SYNTHESIS

The organization of the synthesis is derived from two sources. The first was a research effort by Roden (*4*). The second source was a discussion held by the NCHRP synthesis panel. Both suggested ways to organize the integration of GPS data into a GIS. Roden's software manual presents the integration process as the following five-step procedure (Figure 4): (1) data collection, (2) data review, (3) data smoothing, (4) map matching, and (5) data summary. Although Roden's manual does not indicate how the steps should be accomplished, his method is significant because it helps to understand the overall process.

The synthesis panel viewed GPS–GIS integration as a three-step process: (1) data collection, (2) data reduction and smoothing, and (3) map matching. The six-step method presented in this synthesis was developed from these two approaches.

CHAPTER TWO

PROJECT PURPOSE AND GIS BASE MAP SELECTION

INTRODUCTION

This chapter addresses the first step in the GPS–GIS data integration process. It explains the relationships between project purpose and GIS base map selection. It is essential that an identified project purpose or set of project objectives determine the appropriate GIS base map that supports GPS data collection techniques. A universally accepted statement of good practice indicates that project purpose and objectives should be stated as clearly as possible.

PROJECT PURPOSE

Two factors dictate that project purpose determines the way GPS data are collected and the type of GIS base map used for a project: the required spatial accuracy and the frequency of data points collected. Any project requires a predetermined level of spatial accuracy. This must be determined prior to data collection in the field. Crews collecting data must know the procedures needed to meet the data accuracy and frequency standards.

If general-purpose GPS equipment and software are used, a second factor must be considered: the number or frequency at which GPS positions are collected. It may be that data can be collected every second, but this may not be necessary or desirable. If equipment and software customized to the application are used, many of these limitations are eliminated.

Without knowledge of the required project spatial accuracy and frequency of data collection points, it is highly likely that time and money will be wasted in the data collection effort and that data will have to be re-collected. For example, collecting speed data might require a data point every second, whereas tracking the location of a bus may require a data point every 15 s. The spatial accuracy for the speed study may be within 3 m, whereas that of the bus may be within 10 m of its actual position.

For different types of studies, including corridor identification, fleet management, speed studies, or travel surveys, the objectives are different; hence, the data collection techniques may also vary. A comparison between data collected for a speed study and a travel survey can demonstrate the point. Differential correction and a large number of uninterrupted data points provide more accurate positions for use in speed calculations, acceleration/deceleration rates, and stop conditions (*5,6*). A travel survey may or may not require this data correction technique to obtain satisfactory results depending on the level of spatial accuracy required (*7*). Therefore, it may be possible to use raw GPS data to satisfactorily match auto route choice to a GIS base map (*8*). This is especially true with selective availability (SA) deactivated.

It is incumbent upon a project manager to ensure that everyone is aware of the objectives of the project so that the rate of data point collection and the required accuracy levels are attained. With these parameters established, the project can move to the data collection phase.

The required accuracy of GPS points collected by 19 DOTs varied tremendously. GIS analysts and planners stated that their requirements for spatial accuracy of static GPS data included 3 m, +5 m, less than 10 m, less than 20 m, and less than 25 m. Surveyors demanded a significantly higher level of accuracy for static GPS. All of their standards require accuracy of less than 1 m. DOT surveyors reported working with accuracies of less than 5 cm, 1–3 cm, 2–4 cm, and 1.2 cm or less.

It is important to know how well GPS points fit into the GIS base map. The base map must be in place before data collection begins. The literature reviewed did not identify this step as an early requirement in the process. Most base maps were accepted as a given in projects. For example, many mapping projects used the U.S. Census Bureau's Topologically Integrated Geographic Encoded Reference System (TIGER) map files or some commercial substitute without regard to map scale, datum, projection, or map accuracy (*9*). The TIGER files were originally created as a digital base map for use by the U.S. Census Bureau to assist the agency in its efforts to collect and view census data. As such, the spatial accuracy of the TIGER maps was not a primary concern. The TIGER maps are based on the 1:100,000 series of paper maps from the U.S. Geological Survey (USGS). The source maps used the North American Datum of 1927 (NAD27) for the horizontal datum. Accuracy problems between GPS points and the map can result if one is not aware of the original scale and datum.

Given the short amount of time that most DOTs have used GPS and GIS, their rules and standards are limited and often borrowed from another agency or company. Some agencies in the mapping context, not surveying, are using projections and datums without much thought to what they mean. It appears that in many cases the software drives the mapping procedures rather than staff selecting these critical map elements with the project purpose in mind.

It is not surprising that some DOT staffs have a difficult time using TIGER or other map bases to match GPS points. GIS base map selection is critical for a good fit between GPS points and the GIS base map. Consequently, base map selection should be given more thought relative to project purpose and should be considered early in the project timeline.

GIS BASE MAP SELECTION

Cartographers have long known that maps include error. Maps can be distorted in such a way as to "lie" about the data being represented (*10*). Map creation involves a series of choices about how features will be represented, and each choice can introduce error. The steps in the process include choice of (1) scale, (2) level of generalization, (3) projection, (4) datum, and (5) coordinate system (*11*).

Map Scale

When discussing map scale and travel surveys, address matching, or almost any transportation-related issue, bigger is better. The GIS analyst should ask, what would be the most important use of the digital base map? If the base map is used for project work (which is unlikely), its scale will have to be significantly larger than if the only work to be done with the map is system wide. In addition, the project level map will require a higher level of spatial accuracy than a system-wide map.

Maps scales are divided into three general categories—large, medium, and small. Large-scale maps begin at anything less than 1:1 and continue to 1:24,000. A typical large-scale map is a highway project map at a scale of 1 in. represents 500 ft (1:6,000). Medium-scale maps range from 1:24,000 to 1:100,000. One of most commonly used 1:24,000 scale maps is the USGS topographic quadrangle. Anything smaller than 1:100,000 is considered small scale. Figure 5 shows the effect of changing map scale on the amount of detail. For example, "maps for ITS applications may be at scales of about 1:5,000 to 1:10,000 in cities (similar to those used in 'street directories') and at smaller scales along the major roads outside metropolitan areas" (*12*).

As Figure 6 shows, map scale can be related to GPS accuracy. As the map scale becomes larger, accuracy requirements increase, as do the sophistication of GPS algorithms and equipment.

Scale is an issue, because as scale becomes larger the amount of detail presented in a map can be increased. The ability to measure the length of linear features, the position of point features, and the areas of polygons with a high level of accuracy are also increased. As the scale is made larger, it requires higher levels of accuracy and less error.

An NCHRP Research Results Digest recommended scales for different types of projects. DOTs should plan to support four different scales (Figure 7) (*13*). They include small scale 1:500,000 for statewide planning, 1:100,000 for district level and facilities management, and 1:12,000–1:24,000 for corridor planning and preliminary engineering over a large area. The largest scale is 1:120–1:2,000 for mapping at the project level. This level of mapping is not amenable to an area-wide GIS, but the GPS positional data from it could be used to upgrade other maps.

Level of Generalization

The next choice is the level of generalization that will be applied to the features of the map. Generalization is affected by two independent factors, first by the selection of scale, and second, by a qualitative decision about what information is to be communicated to the map reader. Whenever the surface of the earth is represented on a map, the features are generalized to some degree. Roads are represented as a single "centerline," eliminating small curves or dropping out features (on–off ramps) so that maps are legible. However, generalization distorts the features on the ground and introduces error. For example, US Highway 1 along the California coast, with a changing road width and numerous curves, becomes a smooth centerline road at scales of 1:62,500 or greater.

Generalization is also influenced if the mapmaker decides that one set of information is less important than another. For example, suppose there is a need to create two maps at the same scale; a central business district (CBD) traffic map and an accessibility map of the same CBD. The first map could show traffic flow and turning movements by lane. The second map would not only show the traffic, but it may also show pedestrian movement on the sidewalk, bicycle movement in the street or in bicycle lanes, and transit movement on the street or in separate diamond lanes.

Projection

The third step is choice of map projection. Projection determines how the features on the curved surface of the earth are transformed and represented on a flat piece of paper or a computer screen. For small area studies this is often not an issue; however, when trying to line up two maps,

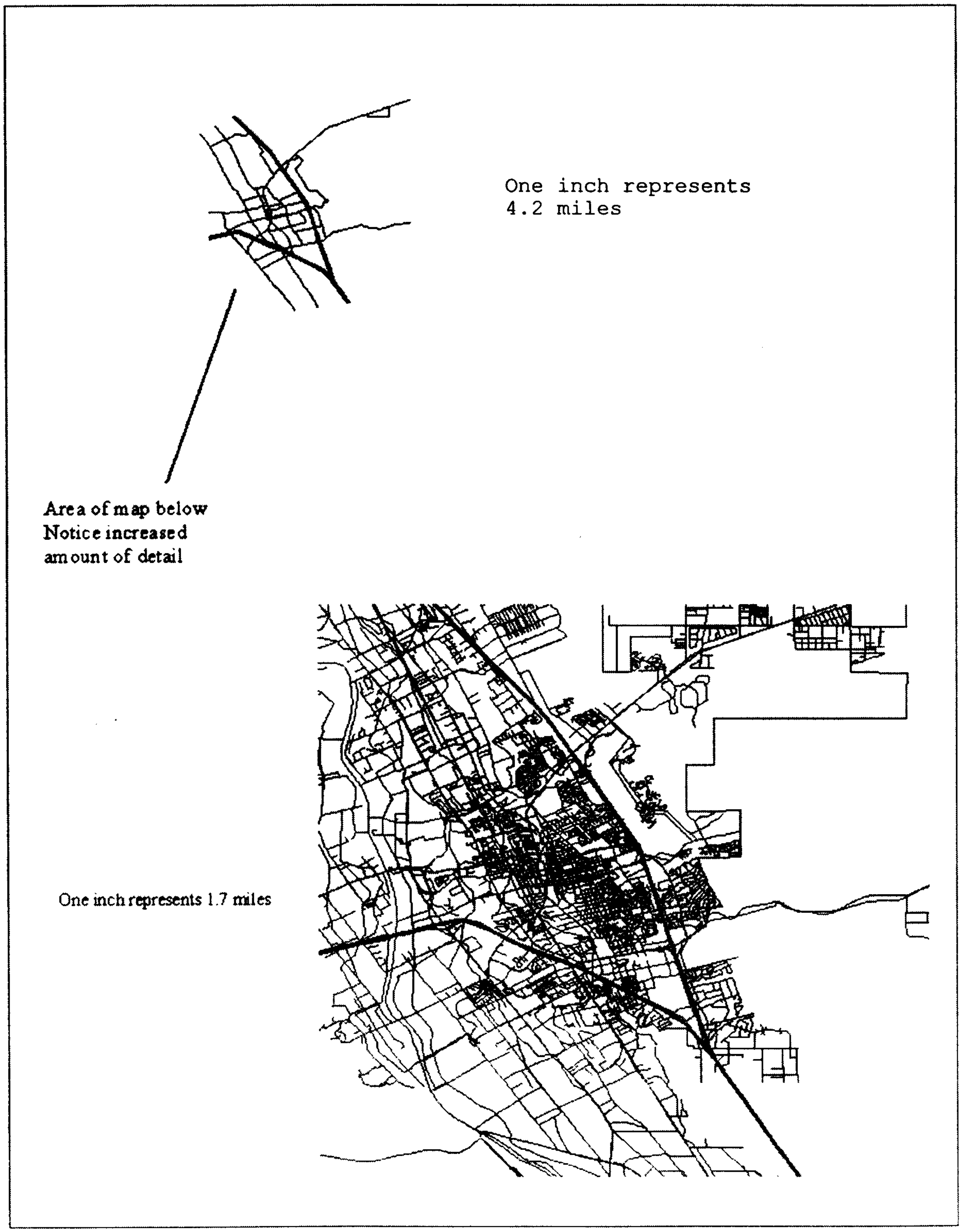

FIGURE 5 Effect of scale change on amount of detail.

each in a different projection, the result can often be mismatched points.

There are many map projections. The most common projection used by state DOTs is the Universal Transverse Mercator. The second most common is the state's own State Plane Coordinate System. Some of the DOTs also use Lambert Conformal and Albers Equal Area projections. Changing a map projection means simultaneously changing the relationships of area, shape, and direction on a map (*14*). Each of these factors can introduce error into the representation of a point, line, or area on a map (Figure 8).

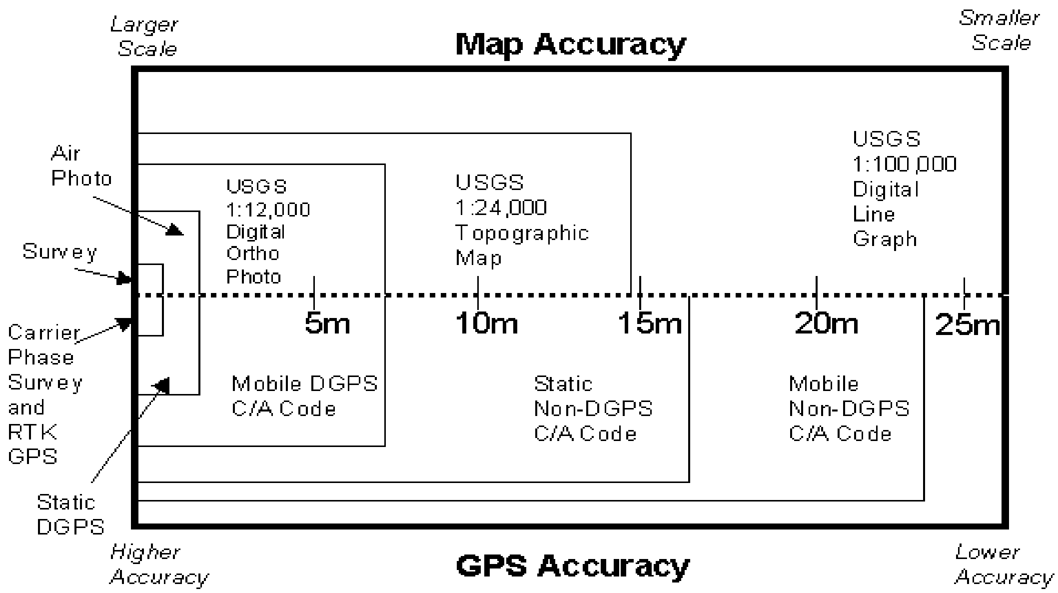

FIGURE 6 GPS and GIS accuracy (at 95 percent confidence interval) (source: Bob Lewis, Navstar Mapping Corp.).

Geographic Extent	Typical Activities	Digital Map Base Scale	Digital Map Base Precision (ft.)
State	Statewide Planning	1:500,000	830
Multi-district	Corridor Planning		
District	District Planning	1:100,000	170
Metropolitan Area	Facilities Mgmt.		
		1:12,000–1:24,000	30–40
	Corridor Analysis		
Project	Engineering Design		
	Construction	1:120–1:1,200	0.33–3

Increasing Centralization

FIGURE 7 Relationships among geography, activity, scale, and accuracy (after NCHRP 20-27, October 1993).

Horizontal and Vertical Datum

The fourth choice that may introduce error is selection of horizontal and vertical datum. Datum is defined as any quantity or set of such quantities that may serve as a reference or basis for calculation of other quantities (*3*). Although datum is more of an issue for surveyors than mappers, as map scale becomes larger, datum can have a serious effect on the placement of GPS points into a GIS base map. Both horizontal and vertical datums in the United States are calculated by the National Geodetic Survey (NGS).

The horizontal datum is represented by an ellipsoid; a mathematical calculation of the shape of the earth from

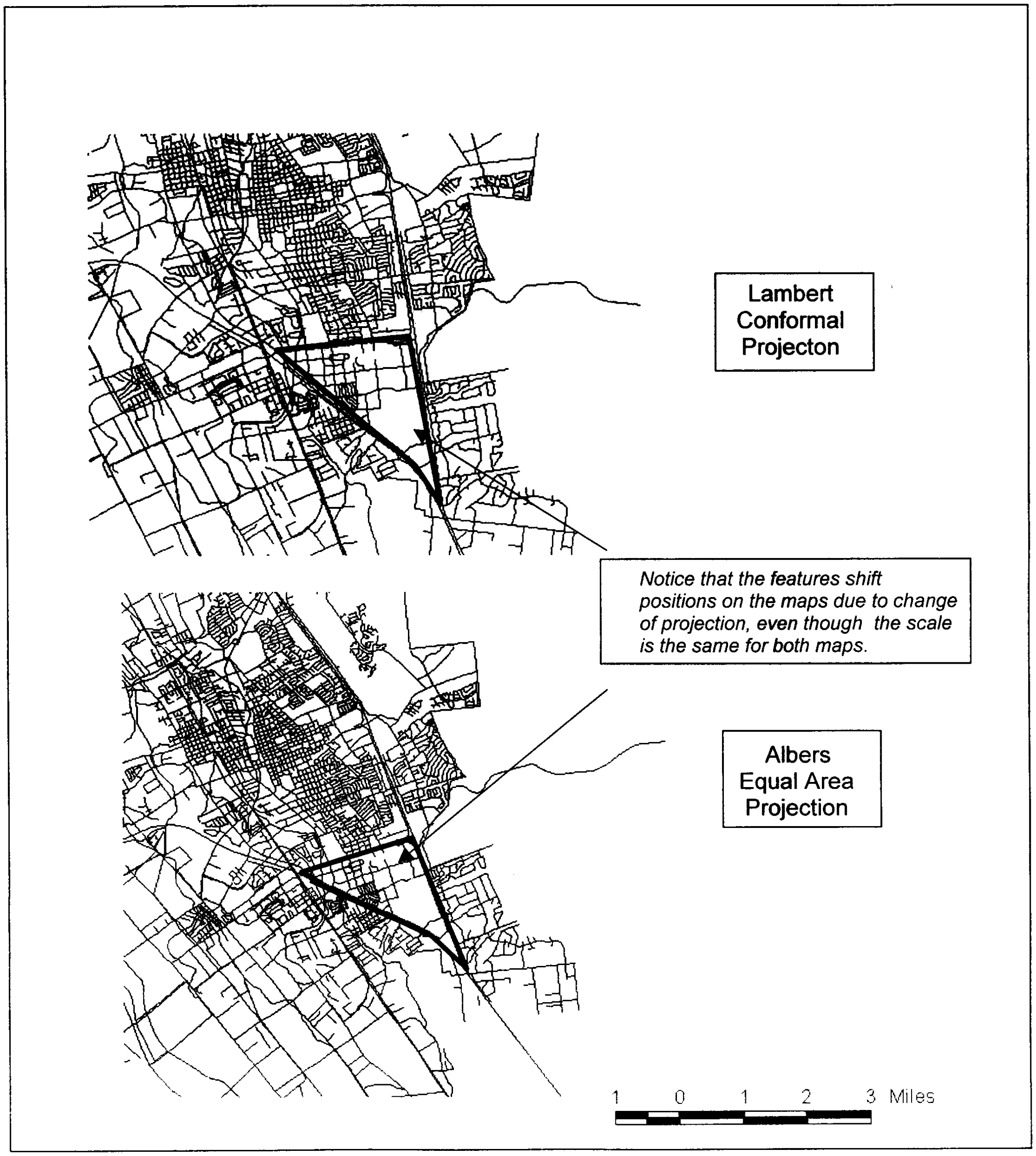

FIGURE 8 Effect of projection on the relative position of features.

which we take "*x* and *y*" positional measurements. Its most significant effect is on maps at large scales, especially when two different datums are used. Depending on what shape we calculate, the *x* and *y* position will slightly change. The most common horizontal datums used by DOTs are the North American Datum of 1927 (NAD27), the North American Datum of 1983 (NAD83), or NAD83 adjusted in 1986.

The NGS is responsible for maintaining and upgrading the National Spatial Reference system (NSRS), a nation-wide reference datum. This very high accuracy reference network of permanently marked control points is located at approximately one degree latitude by one degree longitude throughout the United States and its territories. There are additional stations where needed for safe aircraft navigation and crustal motion. Between 1987 and 1997, NGS updated the horizontal and ellipsoid height components of NSRS through the development of the statewide High Accuracy Reference Networks (HARNs). Examples of existing HARN networks include Minnesota, Texas, Florida, Mississippi, and New Mexico.

The purpose of the HARNs and the NSRS is to improve the status of existing geodetic control networks and to support growing GPS applications (*15*). An additional system for improving GPS accuracy is the continuously operating reference system (CORS). The CORS is a nationwide network of continuously operating base stations set up under the coordination of NGS. The system provides significantly increased accuracy for code range and carrier phase GPS measurements. Examples of statewide CORS can be found in Texas, Pennsylvania, Vermont, Virginia, and Florida.

One of the most significant reasons for establishing the high-precision networks is the growing development and implementation of DOT and MPO GIS systems. High-precision networks provide improved database correlations and increased positional integrity of GIS data over the long term. They will also improve the usability of data exchange between governmental and commercial GIS information. In addition, they will improve the ability of DOTs to link individual project surveys together to build accurate large area maps. Over a period of time this has the potential to significantly improve GIS base maps. Vertical datum in the United States is measured from the North American Vertical Datum of 1988 (NAVD88). The vertical datum is the mathematical surface from which elevation is measured. NAVD88 is not a sea level datum; its origin is Father Point on the St. Lawrence River at Rimouski, Quebec, Canada. Vertical datum is rarely an issue for thematic mapping (unless digital elevation models or satellite imagery is used), but it is critical in surveying. The most common horizontal datum used by DOTs is NAD83 or NAD83 adjusted in 1986.

Coordinate System

The final step is the coordinate system. Most DOTs use the state plane coordinate system, the metric system of Universal Transverse Mercator, or latitude and longitude. In addition, local coordinate systems are used for small area projects.

MAPS IN A GIS ENVIRONMENT

Making maps in a GIS environment poses a series of challenges, the least of which is changing from an analog mode to a digital mode of map design and creation. The majority of transportation agencies have made this switch. For some it was straightforward, whereas for others it was a painful and expensive process, sometimes done more than once to obtain useful map products.

Here the concern is with problems that are generated by operating in a digital environment that may create errors in mapping. The DOT or MPO should address four major issues: (1) map acquisition, (2) metadata, (3) digital map scale, and (4) vector or raster base map.

Digital Map Acquisition

Acquisition or creation of the digital base map is the first concern. Although there are many data sources, some are clearly better than others. The least desirable source for a base map is unidentified and unspecified digital data. Data of this type may be highly accurate or highly inaccurate, one cannot be sure. Without specifications for the data, there may be hidden errors that will only be noticed by chance.

Metadata

The only way to address the requirement for specifications is with metadata, data that should be identified in a separate file (similar to a header file for a satellite image) with the digital map indicating its source, original scale, data accuracy, and other map characteristics. To avoid hidden errors, the best choice for a digital map base is to locate an existing digital map file that has metadata tied to it. A correctly structured metadata file indicates the amount of spatial error within a map. A metadata file also provides basic information such as datum, projection, and the coordinate system used to make the map.

According to the synthesis survey, metadata are used by 16 DOTs. The metadata file contents are derived from one of four sources. The most common source is in-house standards (most likely adopted from a mix of the following four sources). The other sources for metadata standards are the Federal Geographic Data Committee, National Standard for Spatial Data Accuracy, and NGS. Thirteen agencies do not use metadata. Accuracy verification of DOT maps without metadata is accomplished by comparing digital maps to digital orthographic photo quarter quadrangles, in-house maps with a known level of accuracy, and visual overlay of the NGS monuments. One agency reports that if they are using a nondocumented map, they contact the mapmaker or publisher for information. Metadata are not widely used by transportation agencies; it is still a relatively new concept in mapping. It will become more common for state agencies, especially if the federal government decides that all mapping accomplished with federal monies will require metadata. (Appendix D provides metadata standards from the Tennessee DOT.)

Digitizing Paper Maps

A less desirable source is to create digital maps from paper maps. Not only may the paper map be in error, but digitizing (entering data using a digitizing tablet and puck) has its own inherent error that most likely will increase the error of the digital map.

The 1:100,000 source maps for the U.S. Census Bureau's TIGER maps provide an example. When the Census Bureau digitized the USGS paper topographic maps, a misalignment of the digitizing puck by 0.05 in. from a line on the paper map changes a point's position by 416 ft on the new digital map. This type of map error is common when digitizing a paper map. An additional unseen error can be derived simply by a change in a room's humidity, because paper is an unstable base and will shrink or expand. Digitizing from Mylar, a stable base material, can reduce this type of error.

Vector or Raster Base Map

The second choice for the GIS technician is to decide whether to use a vector or raster base map. A map built with a vector model uses *x* and *y* coordinates to locate nodes, arcs, and polygons. A raster model divides a map into rows of individual squares or pixels, with each square filled with a measured attribute value. Overwhelmingly, the vector model is the choice of transportation agencies; however, with the introduction of satellite imagery and orthophotography into our "tool bag," raster data become a more important consideration.

MAP ACCURACY

A final issue for digital base maps is accuracy, which can be measured four different ways.

- Absolute accuracy,
- Relative accuracy,
- Attribute accuracy, and
- Temporal accuracy.

The most common accuracy measure is absolute accuracy or the relationship between a geographic position on a map compared to its real world position measured on the surface of the earth. This is most important for larger scale maps, especially those mentioned earlier at the largest engineering project scales.

U.S. National Map Accuracy Standards

Historically, absolute spatial accuracy for many federal and state projects has been influenced by the U.S. National Map Accuracy Standards (NMAS) of 1947 (*16*). The standard required the horizontal component of the map to meet the following conditions:

> Not more than 10 percent of the tested points should err by more than 1/30th inch at publication scale for map scales larger than 1:20,000, or not more than 10 percent of tested points should err by more than 1/50th inch at publication scale for maps 1:20,000 and smaller. In addition, the vertical component is defined by contour interval—not more than 10 percent of tested elevations should be in error by more than one-half of the contour interval (*16*).

The NMAS is important because, since the end of World War II, it has been one of the few accuracy standards used by agencies to construct paper maps. Digital maps that were constructed from maps using the NMAS, such as USGS 1:24,000 topographic maps, could have accuracies less than the NMAS due to random digitizing error that could be incurred during the digitizing process. Digital maps that were constructed from maps not using the NMAS may have higher or lower spatial accuracy errors.

National Standard for Spatial Data Accuracy

More recently paper and digital map products from federal agencies and agencies using federal dollars have been subject to the National Standard for Spatial Data Accuracy (NSSDA) (*17*). Positional accuracy using the NSSDA was developed during the 1990s by the federal government with support from academia. It recommends a testing and reporting procedure for determining the horizontal and vertical accuracy of maps and digital spatial data. The accuracy statistic allows users to determine if a set of data is appropriate for a given application. Agencies are encouraged to specify their own thresholds for given applications. One accuracy level may be appropriate when determining the route of an automobile, whereas another level of accuracy may be needed when determining the route of a pedestrian; there is no established fixed standard. The NSSDA is a quality indicator of a map's accuracy. A typical NSSDA accuracy statement reads, "Tested 25 (feet or meters) horizontal accuracy at 95% confidence level." A similar statement is used for vertical accuracy.

The method for determining the NSSDA horizontal accuracy statistic is easily accomplished. It requires a six-step procedure.

1. Select 20 test points (*x, y*) and 20 map points (*x, y*), both based on a common datum.
2. Calculate the differences between map points and test points.
3. Calculate the sum of the set of squared differences between map data and test data.
4. Calculate the average of the sum by dividing the sum by the number of test points being evaluated.
5. Calculate the root-mean-square error (RMSE), which is simply the square root of the average.
6. Calculate the NSSDA statistic by multiplying the RMSE by a value that represents the standard error of the mean at the 95 percent confidence level—1.7308 for horizontal accuracy and 1.9600 for vertical accuracy.

It is recommended that a minimum of 20 random points on a map be compared with a set of test points at a known level of accuracy that is significantly higher than what is needed (*18*). The selected points should be visible and/or recoverable. For small-scale maps, typical points include right angles of roads, intersections, railroad crossings, corners of structures, and small isolated vegetation. For large-scale products, points could be selected from centers of utility access covers, intersections of sidewalks with curbs or gutters, or survey monuments.

Table 1 provides an example of the calculation of the NSSDA statistic. For the sake of simplicity, this example uses 10 points rather than the 20 points required by NSSDA. The calculation requires that map points and test points (of significantly higher quality) be matched to one another (map point *x* to test point *x* and map point *y* to test point *y*).

The following equations are used to calculate the NSSDA statistic:

1. $\Sigma[(MPX - TPX)^2 + (MPY - TPY)]^2 = 3156.5$
2. Average = (Equation 1)/10 points = 315.6
3. RMSE = $\sqrt{\text{Equation 2}}$ = 17.8
4. RMSE × 1.7308 = 30.8

In step 4, the factor 1.7308 is applied to circular error at the 95 percent confidence interval, provided that error in each *x* and *y* component is normally distributed and the error for the *x* component is equal to and independent of the error for the *y* component. Vertical error at the 95 percent confidence level is estimated using a similar RMSE equation, where *x* and *y* are substituted by a *z* component. The result is multiplied by 1.9600 (*19*).

In this case, the NSSDA statement reads, "Tested 30.8 feet horizontal accuracy at 95% confidence level." Whether this isacceptable or not is a decision that must be made by the map data user. If it is not acceptable, the user must find another source or contact the agency that made the map to determine if there is a way to increase accuracy.

Relative Accuracy

Another type of accuracy is relative accuracy, which refers to the displacement of two points on a map (both distance and angle), compared with the displacement of the same points when measured on the earth's surface. Relative accuracy is often more important than absolute accuracy. It is easier to specify because users rarely need to know absolute locations.

Attribute and Temporal Accuracy

Attribute accuracy means the completeness of the attribute database records linked to a GIS's mapped features. Attribute accuracy is most important to users with complex data needs such as modeling. In addition, users must be concerned about the currency of the map and database. Anyone concerned about improving the quality of their digital base map should use project GPS position locations and add them to their corridor or system-wide maps to increase their accuracy.

It should be clear from the list of potential sources of error and applications of GIS/GPS integration that the heart of the problem is to develop and maintain a current database and a spatially accurate digital base map.

For example, according to Ohnishi and others (*20*), the most important element of a vehicle navigation system is an accurate base map. They identified the following set of characteristics for a multi-functional navigation system map:

TABLE 1
NSSDA CALCULATION TABLE

Map Point X MPX	Map Point Y MPY	Test Point X TPX	Test Point Y TPY	MPX – TPX	MPY – TPY	Difference Squared
573351	71242	573352.3	71248.8	–1.3	–6.8	47.9
581587	70596	581574.8	70577.6	12.2	18.4	487.4
584799	70327	584789.4	70325.1	9.6	1.9	95.8
600163	72565	600161.9	72582.4	1.1	–17.4	304.0
592806	76380	592813.4	76360.9	–7.4	19.1	419.6
586980	76478	586978.1	76463.4	1.9	14.6	216.8
587408	80269	587410.2	80279.3	–2.2	–10.3	110.9
581639	81779	581606.9	81777.7	32.1	1.3	1032.1
571375	77040	571377.9	77060	–2.9	–20	408.4
574797	83172	574793.6	83176.7	3.4	–4.7	33.7
				Sum of the squared differences		3156.5
					Average	315.6
					RMSE	17.8
				NSSDA horizontal statistic		30.8

- Accuracy equivalent to 1:25,000 topographic maps,
- All road networks of 3 m or wider,
- Route database for searching a recommended route,
- Intersection diagram data for route guidance, and
- Data indexing location names.

The identification of project purpose and selection of the GIS base map are only the beginning of the process to integrate GPS and GIS. If these two steps are completed with care, the next step, collecting GPS points, can be accomplished efficiently and effectively.

CHAPTER THREE

GPS DATA COLLECTION WITH AN EMPHASIS ON MOBILE GPS COLLECTION TECHNIQUES

INTRODUCTION

This chapter provides an overview of GPS data collection processes and describes how differential GPS (DGPS) correction can be used to improve GPS data accuracy. The meaning of accuracy in GPS data collection is explained, and considerations for improved GPS data collection from the literature are discussed.

All of the research from the literature discussed in the synthesis was completed prior to May 1, 2000. On this date, President Clinton deactivated a feature on the national GPS system known as selective availability (SA). The purpose of SA was to degrade the accuracy of the GPS satellite signals. With SA deactivated, GPS receivers can provide higher accuracy positioning than ever before. This is discussed later in the synthesis. The effect of the President's action would allow improved positioning in most of the research discussed within the synthesis. For example, some applications that required differential correction may no longer require it.

STATIC AND MOBILE GPS

The collection of geographic positions is accomplished with a GPS receiver that determines the position of a GPS antenna using trilateration and solves for four unknowns—the x, y, and z coordinates and the difference between the satellites clocks and the GPS receiver's internal clock. To determine a location on the earth's surface, a sphere for each satellite–GPS receiver communication link is identified. The intersections of three spheres, requiring three satellites and one receiver, specify two points, one in space and one on the earth's surface. The intersection in space is ignored; the intersection on the earth's surface is the GPS antenna position. To eliminate clock drift, a minimum of four satellites (four spheres) are required to determine x, y, and z positions. If only x and y positions are required and a constant z (elevation) value can be assumed then three satellites will suffice (*21*).

When a GPS unit is placed at a single location for a period of time it collects numerous data points. This is called static data collection. The points can be used to calculate an average position.

The simplest and least expensive form of GPS data collection uses a coarse acquisition or C/A code, pseudorange, or standard positioning service GPS receiver. Generally, it will provide accuracy in the 15–25 m range. This is the type of receiver commonly used by mappers, GIS analysts, and transportation planners.

DIFFERENTIAL GPS

The accuracy of both static and mobile GPS data can be improved with differential correction. Differential correction can be accomplished in real time or data can be post-processed later on a computer. Real-time differential correction is accomplished by using a GPS receiver placed at an established surveyed position, Point *A* (Figure 9). In real-time differential correction, the corrections are calculated at the receiver (Point *B*). The receiver at *B* will use the broadcast signal from *A* in real time to correct the position at *B* and generate a more accurate set of coordinates.

Real-time DGPS is being made widely available through the development of the Nationwide Differential GPS (NDGPS) program. In 1997, seven federal agencies, with support from state governments and coordinated by the U.S. DOT, began planning for a DGPS system to provide nationwide coverage including Alaska, Hawaii, and Puerto Rico. Real-time differential corrections will be broadcast around 300 kHz. Once fully operational, the NDGPS will cover the nation with the most accurate and reliable navigation system that the country has ever had. GPS users, both civilian and government, will have free access to the NDGPS (*22*).

Post-processed differential correction can also be accomplished by taking GPS data from the receiver at Point *B* and processing the data on a computer at a later time using corrected data in files from a GPS base station. In this case, the corrected data are placed into a computer file rather than being broadcast over a radio or satellite frequency in real time.

MOBILE GPS

GPS data can also be collected while a vehicle is in motion. Collecting GPS points without differential correction can provide adequate positioning for some applications. An example is to track a vehicle's general position using a dashboard-mounted antenna and reporting the results on a

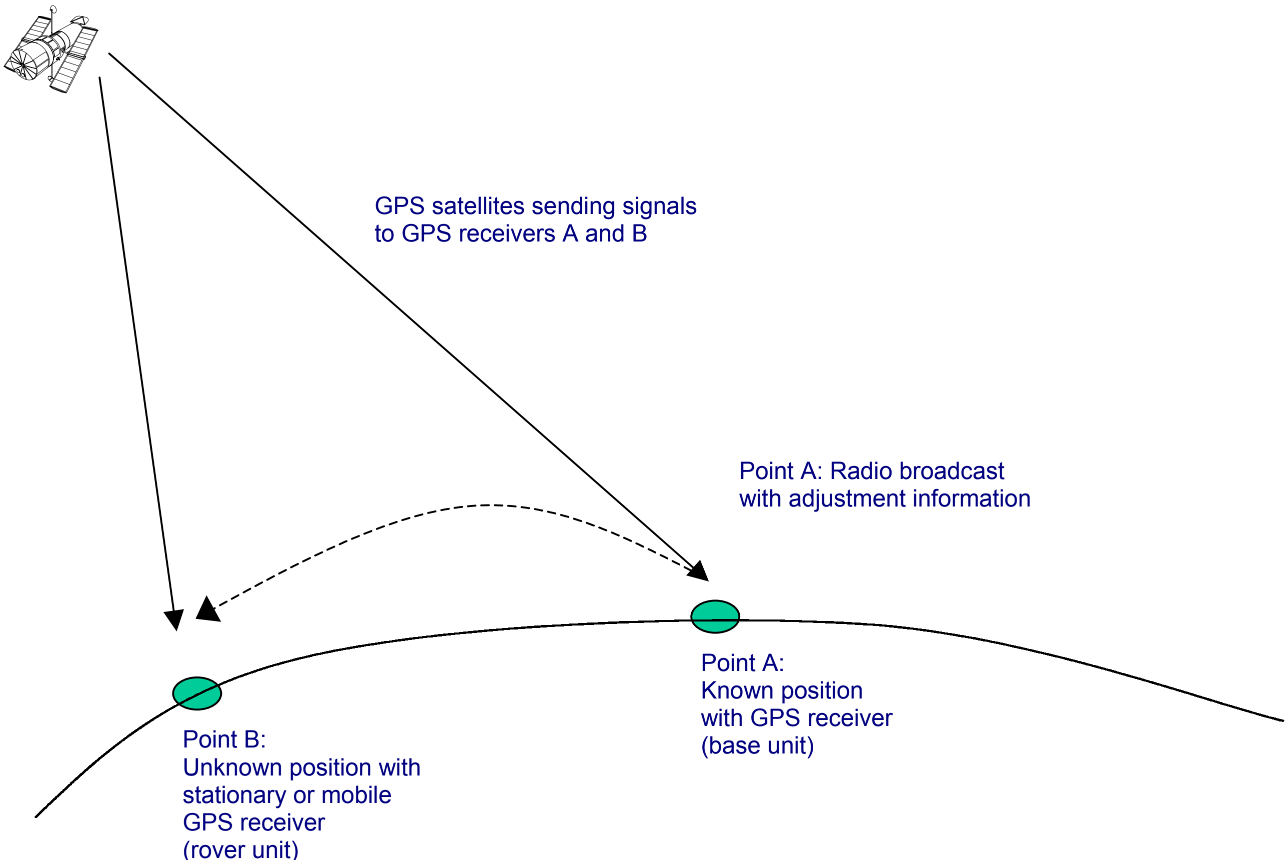

FIGURE 9 Real-time differential correction of GPS signal.

lap top computer. Mobile GPS data collection means gathering differentially corrected points while the GPS unit is located in a moving vehicle. The obvious disadvantage to in-motion data collection is that only one point will be collected for a given position. Averaging data points is not possible.

REAL-TIME KINEMATIC GPS

Real-time kinematic GPS can significantly improve the accuracy of GPS positions for limited mobile surveying applications. Real-time kinematic GPS also uses two receivers—a base station and a remote station in motion. As with DGPS, the C/A code correction information from the base station is transmitted to the remote station. The carrier phase measurements from the base station to the remote station are also transmitted in real time. This allows the remote station to perform survey quality computations in static and limited mobile modes of operation.

DOTS USE OF STATIC AND MOBILE GPS

The collection and use of mobile GPS points among the DOTs surveyed is not a common technique for road inventory and GIS base mapping. Three agencies reported that they do not collect any mobile GPS data, 20 agencies gave no response to the question, and 5 agencies stated that they use the technique for fleet management, snow plowing, road centerline determination, or road alignment inventories. Other uses include topographic surveys, skid-resistant point locations, and horizontal/vertical survey control.

ERROR IN GPS

GPS measurements, whether by pseudorange, carrier phase, or Doppler frequencies, can be affected by error. The error can be additive so the combined magnitudes can affect the accuracy of a specified position. It is important to understand the nature of error and the difference between errors and mistakes. Buckner states (*22*)

> Error pertains to measurement—that is, to estimating anything where exactness is not possible. Errors are unavoidable even to the most thoroughly trained and motivated measurer. They occur to some extent in virtually every measurement because of imperfections of instruments and people, as well as influences of the natural environment.

Buckner also points out that there are two types of error—systematic and random. Systematic errors, those that obey a physical or mathematical law, can be corrected.

Random errors are unavoidable, and may be the result of mistakes in calibration or reaching the limits of a measuring instrument (*23*). GPS devices and GIS maps are both spatial tools that can include systematic and random errors. Adjustments can be made for systematic errors, but agencies must learn to live with specified levels of random error and mistakes ("goofs or blunders").

Understanding the difference between errors and mistakes will lead to better data collection and less frustration. Mistakes occur because of a lack of sufficient information or an inattention to detail. Selecting the wrong symbol for a map to represent a wetland or indicating a map scale as 1:42,000 when it should be 1:24,000 are both examples of mistakes. Mistakes should be minimized and methods developed to eliminate or significantly reduce them.

Systematic error can also be significantly reduced; unfortunately, random error will always be present at some level. The question is, what level is acceptable.

There are a number of factors that can affect GPS error (*3*). The list presented here is not exhaustive, but gives a good idea that collecting accurate GPS data is a process that requires a well-trained, experienced individual.

An error source that affected all of the above collection techniques was SA. It had the potential to degrade the accuracy of the raw GPS signal to approximately 100 m. SA was originally established on selected GPS satellites on July 4, 1991 (*24*). On May 1, 2000, by Executive Order of President Clinton, SA was deactivated, increasing the accuracy of standard positioning system receivers from 100 m to less than 20 m, 95 percent of the time (*25*). No standards for Precise Positioning Code (PPS) receivers had been calculated as of July 2000.

Other sources of error include

- Satellite error
  - Satellite clock errors (tiny differences in the satellite clock can mean serious measurement error).
  - Ephemeris error (error from satellite drift).

- Atmospheric error
  - Ionosphere error (upper atmospheric interference with a signal).
  - Troposphere error (lower atmospheric interference with a signal).

- Operator error
  - Driving on wrong side of road (dozing while driving).
  - Poor planning.
  - Lack of training.

- Limitations on GPS
  - Inability to average data points from a mobile GPS.
  - Receiver error (error from measurement and computation of satellite position).
  - Multipath error (error from satellite signals arriving later than a direct signal because their direct path was interrupted by an object, that is, a building or vegetation).
  - Dilution of precision error (a lack of satellites, poor geometric configuration of satellites, and/or satellites on horizon).

The error sources can cause serious reduction in accuracy when data are collected in a static mode. When the GPS receiver is collecting data in motion, the potential for error is higher than in static mode. Three error sources are particularly problematic: (1) the inability to average multiple data points collected at a given position, (2) multipath error, and (3) position dilution of precision (PDOP).

One cannot collect multiple data points for the same location while a GPS unit is in motion; therefore, the single data point must be used as "the data point." This issue is less important with SA turned off because the GPS units are more accurate. However, because there is only one point, extra care must be given to collecting a point that is useful (its meaning is understood) and its meaning must be useful (accurate, not redundant, not extraneous) when viewed by data users.

The second issue is multipath error. While in static mode it is easier to avoid obstacles that may interfere with a GPS signal. Collecting GPS data while the receiver is in motion makes avoiding obstacles more difficult because they may be present on the landscape as you drive under or by them. Not only can they interfere with the signal (indicating an incorrect position), but also one may lose the signal lock on the satellite. This would mean a loss of data points and require more time to regain the signal (*9*).

The third issue concerns PDOP. Using a GPS unit in motion is made more difficult because the satellite constellation is changing as the data are collected. If the number of satellites and/or their relative positions are less than required by the GPS unit, they can cause a significant decline in data accuracy.

Most of the potential sources of error can be addressed through carefully planned data collection routes, schedules, and computing algorithms. It is important that care is taken in GPS data collection, because without accurate measurement it will be exceedingly difficult to define the accurate positions of the GPS points within a GIS spatial database.

GPS FIELD EXPERIENCE IN TRAVEL SURVEYS AND ROUTE CHOICE

The three data collection issues identified previously, along with a number of other issues, can be identified from various research efforts related to GPS and travel surveys or route choice selection.

Wolf and others identify three items to consider when undertaking mobile GPS data collection (*26*). The spatial configuration of GPS satellites along with the number of satellites has a major impact on accuracy and completeness. The PDOP provides necessary information on the geometry of the satellites above the horizon. A PDOP value of less than 4.0 is acceptable for mobile GPS data collection (*26*).

The GPS receiver must maintain a constant lock on a minimum of four satellites to receive data. Loss of all satellite connections required 2–3 s to reacquire the signal. During this time, data points could be lost. While the satellite signal is lost, the data collection vehicle could be in a turning movement, a lane change, or a stopped at a light. Any one of the above actions could require data filling later. Wolf mentions that, although the loss may not seriously affect the collection of raw data, differential correction requires "continuous good-quality data" (*7*).

Avoiding multipath error is an important consideration in mobile GPS data collection. This occurs when reflection of the GPS signal generates an incorrect position. Multipath error occurs most commonly when some object has caused the GPS signal to bounce from it to the receiver, causing a longer path for that part of the signal. A longer path means increased time for the signal to arrive at the GPS unit. This generates an inaccurate position measurement.

In some applications, multipath and signal blockage can be reduced by carefully planning routes and/or test driving the routes prior to actual data collection. In other applications, all routes must be driven, so this is not an option. Ideally, the mobile GPS data collection effort should take place during the winter or spring months ("leaf-off" season) to minimize the effect of vegetation on satellite signals. If collection efforts must be made during the summer, extra care will have to be taken to avoid multipath and blockage errors. One of the GPS vendors suggests placing the GPS antenna as far as possible from the edges of the vehicle's roof surface, where the antenna is mounted, to reduce the potential for multipath error (*27*).

The Lexington Area Travel Data Collection Test, completed in 1996, provides more techniques on GPS use for travel surveys (*28*). The study tested hypotheses about the usefulness of GPS and hand-held computers to supplement standard travel survey data collection techniques. It is suggested that nondifferentially corrected GPS data were sufficient in most instances to reconstruct trips on a road network.

The following five data collection problems were identified in the Lexington study:

- More accurate position requirements might require differential GPS.
- Using auxiliary sensors or inertial navigation to supplement GPS can be especially useful in urban canyons and in dense tree cover where stand-alone GPS technology may not be sufficient because the GPS signals are reflected or obscured (*28*).
- If an initial position solution was never established during a trip, data may be unusable.
- Similar to the discussion by Wolf, the GPS receiver loses its lock on the satellite. This also makes the data acquired during the lost connection unusable and it occurrs most often at the beginning of trips, but less frequently in the middle of trips.
- Large shifts occur in positional data—in some cases hundreds of miles away. This may be a random error in the software or it may have been caused by electrical interference with the GPS signal.

These five problems indicate that before beginning a trip, special care must be taken by the driver to allow the GPS receiver to acquire a lock on at least four satellites. Furthermore, short trips, such as those less than 1 min in duration or trips with fewer than 15 valid GPS points collected were not sufficient to allow map matching to occur and were discarded from the set of trips (*28*).

In a more recent study by Wolf and others (*26*), a proof-of-concept approach was taken to determine if GPS data, data loggers, and a spatially accurate GIS land-use database could be used to replace standard travel data collection techniques. Although the trip sample was small (151 trips), the research was able to identify 145 trip destinations. The research provided reasonable results concerning trip purposes: 130 or 86.1 percent of the trips had their purposes identified from the GPS and GIS data. From the 130 trips, 120 or 79.5 percent of the trip purposes were correctly identified. Given that this was a first time test of this technique, the results appear promising.

The research by Wolf and Wagner demonstrate the potential for GPS and GIS in travel surveys. Some of the potential benefits include reduction in respondent burden, reduction in telephone interview costs, extension of survey periods, improved accuracy, and addition of new data elements to the survey process (*26,28*). Even with these results, there is a recognition that some data will still have to be collected by computer-assisted telephone interview

(*29*). Some of the data elements requiring respondent contact include the number of passengers taking a trip, driver identification, and ambiguous results from the GPS data.

In a study by JHK & Associates, concerned with the use of GPS for travel time and speed data, information on the GPS data collection process was provided (*30*). It concludes that

> There is significant variation in the quality of data generated by different GPS receivers. Accurate travel speed data and automated map matching require a GPS receiver that calculates speeds from the Doppler effects of the satellite signals. The receiver should also include internal data smoothing and track at least six satellites simultaneously. Differential correction is useful, but not necessary and not particularly convenient . . . and
>
> The full detail of second-by-second GPS data points referenced to a network facility provides the best information for generating useful performance measures. Statistical variability and weighted averages from aggregate data collection efforts provide the level of information that is needed to address complicated system performance issues. The GPS data processing effort should preserve the detailed information GPS technology provides and use this detail to generate performance measure and data for a wide variety of purposes.

The study also suggests that overestimation in travel distance, reported in a study from Australia (*31*) and a study by the Battelle Institute (*32*), can be reduced by extending the amount of time between GPS data collection points. The error can be reduced by 50 percent by using data at 10-s intervals. Although data collection at longer intervals may be employed to increase accuracy, data should still be collected at the 1-s interval because it may be useful for other positioning applications.

An alternative for collecting speed data is to not calculate speed based on the time and the distance between GPS positions, but to use GPS receivers "which employ Doppler algorithms to obtain speed independent of the position calculations." The authors report that this method provides "far more accurate speeds than those based on position calculations." They also cite two studies that recommend setting a threshold for speeds below which the vehicle is considered stopped (*31,33*). The threshold ranges between 1 and 8 mi/h depending on the accuracy of the GPS reading.

According to Draijer et al. (*34*), travelers in a recent Netherlands test needed to wait up to 1 min before beginning the trip. If the traveler left immediately, the GPS unit, performing in a cold start mode, could experience an origin error or time-to-first-fix error of as much as 1 km from the actual origin. This suggests the need for using alternatives to GPS for calculations of address locations. Two methods are: manually entering origin and destination addresses and obtaining addresses from a personal digital assistant file linked to a GPS where the address is derived from a traditional travel survey. Without this added information, it is likely that if only GPS is used, the final destination of a trip, for example a two-block walk to an office, may be missed.

Even though geocoded addresses are often available in digital map bases, they may be incomplete or an incorrect geocoded address may be identified based on a GPS entry. For example, if someone parks around the corner from their final destination, or enters a parking garage, an incorrect address will be generated by the interaction of the last GPS signal and the geocoded map base.

Draijer and others also identified loss of GPS signal as a problem. Such a loss could cause an underestimation in total travel mileage, because to replace lost mileage a straight-line distance was used to augment the lost data points (Figure 10).

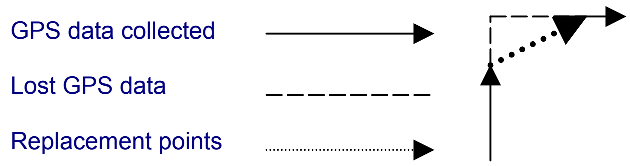

FIGURE 10 Data substitution: Missing GPS points.

Draijer and others also suggest that it is difficult, but not impossible, to collect route data on bus riders. They found that if an individual sits near a bus window on a bus with a GPS receiver, it is possible to collect useful information from a GPS unit. However, the urban canyon problem is still present. Although it is difficult, rail, pedestrian, bicycle, and multimodal travel can also be identified with a GPS: "90% of the car trips were registered, in the case of tram and train this percentage was around 50%" (*34*). The lack of route data on the digital map makes it difficult or even impossible to match the GPS data for the nonauto trips to the map. This is a nontraditional map matching problem and will be discussed later in the synthesis.

As part of its congestion management system, the Northwest Louisiana Council of Governments developed a database using GPS collection techniques in order to calculate accurate travel time and delay data (*35*). They decided to use GPS because it was cost and time efficient. The following standards were used in their data collection efforts:

- Perform travel time runs on nonholiday weekdays (Tuesday through Thursday);
- Conduct runs during off-peak and peak hour travel times;
- Field check all corridors before the actual run to identify overhead obstructions that might block the GPS signal;

- Schedule runs when PDOP is extremely low, such as 2.3 or less;
- Use the floating car technique and drive the corridor at least twice;
- Make sure the base unit includes satellite data that the rover unit is tracking; and
- Conduct runs only during good weather.

DOTS AND GPS DATA STANDARDS

DOTs address the issue of mobile GPS data collection in different ways. Few DOTs have generated their own accuracy standards. Only 10 agencies indicated that they have written formal protocols for collecting static GPS data, while 12 use formal protocols for mobile GPS data collection.

Most agencies have borrowed their standards from other agencies. The sources of standards include the National Spatial Standards for Spatial Data Accuracy from the Federal Geographic Data Committee (*36*), NGS guidelines for the collection of geodetic quality data (*37*), and accuracy standards derived from state statutes and GPS vendor manuals.

Within the DOTs that have developed their own standards, the rules can be specific and lengthy. If a project goal is to achieve accurate and consistent data collection, the rules for data collection must be clear and precise. Some agencies, such as those in Arizona, Tennessee, Oregon, and New York, have manuals that specify how data are to be collected (*38–41*). The Oregon standards are offered as a sample set of standards in Appendix C.

The most common rule used is to avoid multipath error whenever possible. One agency goes so far as to require “an obstruction inventory” prior to the GPS survey being done. Another common rule used to minimize DOP error is to track a minimum of four satellites and maintain a PDOP (the relationship between the error in user position and the error in satellite position) of less than six.

With the completion of the data collection, the next step is to review the data set and correct it when necessary.

CHAPTER FOUR

DATA REVIEW AND DATA SMOOTHING

INTRODUCTION

The third step in the GPS–GIS data integration process is data review and data smoothing. This is a quality control check to verify that the data collected were complete and correct. Without this step, there is a strong possibility that data results will be at best, inaccurate and at worst, useless.

DATA REVIEW

Data review includes identifying missing or bad data. Common problems as derived from survey data include

- Differing coordinate systems;
- Duplicate arcs and lines in base map conflicting with GPS data;
- Lack of training and experience with mobile GPS;
- Finding that areas of the base map are not accurate;
- Some want GPS points off-set from base map while others do not;
- GPS showing base map is incorrect, the map accuracy can be improved;
- Most GIS systems seeming to only work with decimal degrees; and
- Correcting one GIS layer to fit GPS makes other layers inaccurate.

The data review step can also be used to initially determine how well the GPS data fit when overlaid onto a GIS base map. Some of the data will be identified as "bad data" or the data can be interpreted in two ways. There may actually be bad data. As was discussed in the Lexington Area Study, data were mistakenly collected at irregular intervals, making it difficult to determine speeds and, at times, making the route hard to determine (*28*).

It is not only important to be aware that there may be bad data in a database, it is equally important to understand why the data are bad. For example, Guo and Poling state, "If the trace of a GPS run showed a different or incomplete path of the designated route for the run, causes for such abnormality, such as driver negligence, bad GPS signal reception, or improper route definition, were identified and appropriate measures were taken" (*42*). The implication is clear—not only must the data be corrected or eliminated, but the research method must also be examined to ensure that the mistake does not occur again.

The second issue in analyzing bad data is that even though they may appear as incorrect, the problem may be that they are being misinterpreted. For example, if a set of GPS data points indicates a condition where a vehicle has stopped (Figure 11), there could be a variety of reasons why this occurred (*43*). It may be that the vehicle is simply moving slowly because of congestion or it could be stopped at a traffic light. The vehicle could have turned off the road for a brief moment to check a tire, stopped at an automated teller, or picked up someone without turning off the vehicle. Any of these events could cause confusion and cause the analyst to interpret the data points as "bad." The reasons for a number of GPS points appearing in a single location must also be understood. Stop points are not always considered bad points, they may just indicate a normal situation in traffic.

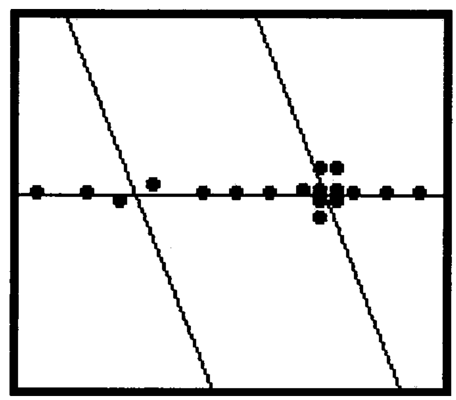

FIGURE 11 Example of stop position from GPS points (*34*).

How do DOTs handle bad GPS points? First, 26 state DOTs did not respond to this question and three more said they do not bother with bad point removal. One agency indicated that if GPS points are considered bad, they are recollected. The most common technique, among the five agencies responding, was to use personal judgment (without agency standards) to eliminate or adjust bad data points. They also reported manually moving bad data to their "correct locations." Three agencies used standards, such as NGS. Five agencies indicated that they replace bad data in post-processing with smoothing algorithms.

Post-processing GPS points is a common technique, with 22 agencies accomplishing this task. Most often they used the software provided by their GPS vendors to post-process data. Three agencies said they did not post-process and 16 did not respond to this question.

Post-processing data, including eliminating bad data points or moving data points, is done for a variety of reasons. (Multiple responses from state DOTs were allowed for this question and responses total more than total respondents.) Nineteen agencies indicated accomplishing more than one task with the post-processing step. The most common reason (reported by 19 agencies) is to identify bad data points for manual deletion. The second most common post-processing task (reported by 16 agencies) is to calculate an average location for a given point (when calculating a static GPS point). The last two options (both reported by 12 agencies) were dropping bad data points and smoothing data. Nineteen agencies did not respond to this question. Only seven agencies had in-house agency manuals to guide their post-processing methods.

Many agencies do post-process data (one of the major concerns of the synthesis) by employing formal rules that indicate how data should be eliminated or adjusted; however, other agencies use informal unwritten rules, including

- Using the closest base station to the project,
- Marking and saving the results of intermediate steps,
- Using the same base station for all files in a given project,
- Collecting mobile GPS data at a rate of one/two seconds, and
- Being careful of start and end times for data collection.

Thirty-seven respondents did not answer this question.

With bad data eliminated, the next data review step is to determine if the spatial mismatch between the GPS points and the base map are acceptable or if the discrepancies are so serious that some type of adjustment is required. This is a judgment call; therefore, a well-defined and consistent spatial rule must be used to determine whether an adjustment is necessary. An example of a quantitative rule would be that if a GPS road intersection point is more than 10 m from the indicated intersection on the digital base it would be moved. An example of a qualitative rule is one where the GPS point will be adjusted if, on the computer screen, the GPS point is visually not on the road centerline.

The use of uncorrected GPS data points was problematic because with SA turned on, a GPS point could be 100 m in any direction from its correct location, but with SA turned off, it is possible to achieve 15-m accuracy without correction. Seven DOTs stated that they use uncorrected GPS data. One agency reported that with SA turned off, it is no longer necessary to correct their data for most applications. This comment was made by a GIS analyst not a surveyor. Fifteen agencies indicate that they still differentially correct data. Ten agencies did not respond to this question.

Another data review decision could be to move the map instead of the GPS points. This occurs when it can be determined that there is a systematic shift with the GPS points and they are assumed to be more accurate than the base map. For example, if all points on the map are 10 m east and 15 m north of their intended locations, the map could be shifted to make the two data sets more congruent. How this is accomplished will be discussed in the next chapter.

Once a decision has been made to adjust data, by moving either the GPS points or the base map, the user proceeds to the third and final step in data collection, which is data smoothing.

DATA SMOOTHING

Once the data review step ensures that the data set is useable, the data smoothing step ensures the data are useful. According to Roden, “Smoothing the GPS data is an important step in preparing the GPS data for network matching or creating logical maps . . . (such as network correction and realignment).” Furthermore he says, “The smoothing algorithms compare

- Speed against distance and time,
- Speed against acceleration/deceleration rate,
- Link distance compared to point-to-point distance from GPS,
- Stop conditions and position wandering,
- Bearings against change in position angles, and
- Changes in bearings at the travel speed” (*4*).

Smoothing is accomplished by setting acceptable limits (determined by the user) on each or all of the above comparisons. If a comparison shows an unacceptable relationship, an adjustment is made. The stop condition that was discussed earlier is an example of how data can be smoothed. Data smoothing is essential because there may be too much GPS data detail for the required task, the data may be confusing, or there may be a need to adjust data based on a set of rules that makes the data more useful. Data smoothing involves four different actions: eliminating extraneous data, eliminating duplicate data, replacing inaccurate data, or adding or synthesizing missing data.

Data may be eliminated because they are unnecessary. If data are collected at 1-s intervals, but a 5-s interval is satisfactory for the task, the other data may be eliminated. For example, a travel agency, using GPS and GIS, is attempting to accomplish two tasks simultaneously. The first task is to test the capability of a GPS unit to identify the position of a bus, and the second task is to locate the bus in real time. For the first task, it is required to retain a 1-s interval; however, for the second task, a 5- or even 10-s interval is adequate.

Eliminating duplicate data is the second task for data smoothing. Duplicate data may have occurred because a route was driven more than once (when only one drive was required). Removing this type of data from the database is usually accomplished by viewing the data and eliminating them manually.

Replacing inaccurate data is the third data smoothing technique. This may be done because the GIS analyst sees a mistake or an algorithm detects it. In either case, a substitute GPS point will be needed to replace it. This can be accomplished through a processing algorithm (*4*) or it may be accomplished manually. The GIS base map may also have inaccurate data. Examples of this include freeways represented by single lines or road links that are broken to insert a street label. These types of mistakes must be corrected manually by the mapper. Because of the dynamic nature of a GIS base map, resulting from changes in road names, creating one-way streets, or opening or closing streets, there is a strong argument for keeping the GIS base map current and accurate.

The last data smoothing task is adding data or synthesizing missing data. Adding GPS points can be accomplished manually or with an algorithm (*4*). Adding GPS points manually is the most common approach taken by DOTs. In addition, missing data has also been identified in the GIS base map. According to Hong et al. (*44*), the most common missing data are a lack of one-way street information; inadequate breaks in links that cross multiple intersections; a lack of address ranges, overpass and underpass, symbology; and missing exits and entrances to freeways. They indicate that procedures to reduce this type of error include

- Classifying streets into categories and checking to see that their attributes are present in the database,
- Adding ramp information,
- Constructing freeway topology (topology identifies the mathematical structure of links and polygons in relation to one another; i.e., right and left sides of a road link or the direction of a road link),
- Checking street segment nodes and links to ensure complete connections among segments and proper identification of intersections, and
- Maintaining accurate data files.

No matter which of the four actions is undertaken, it must occur according to a set of rules consistently applied to the GPS and GIS data sets. The rules should indicate how data could be changed uniformly to make them useful

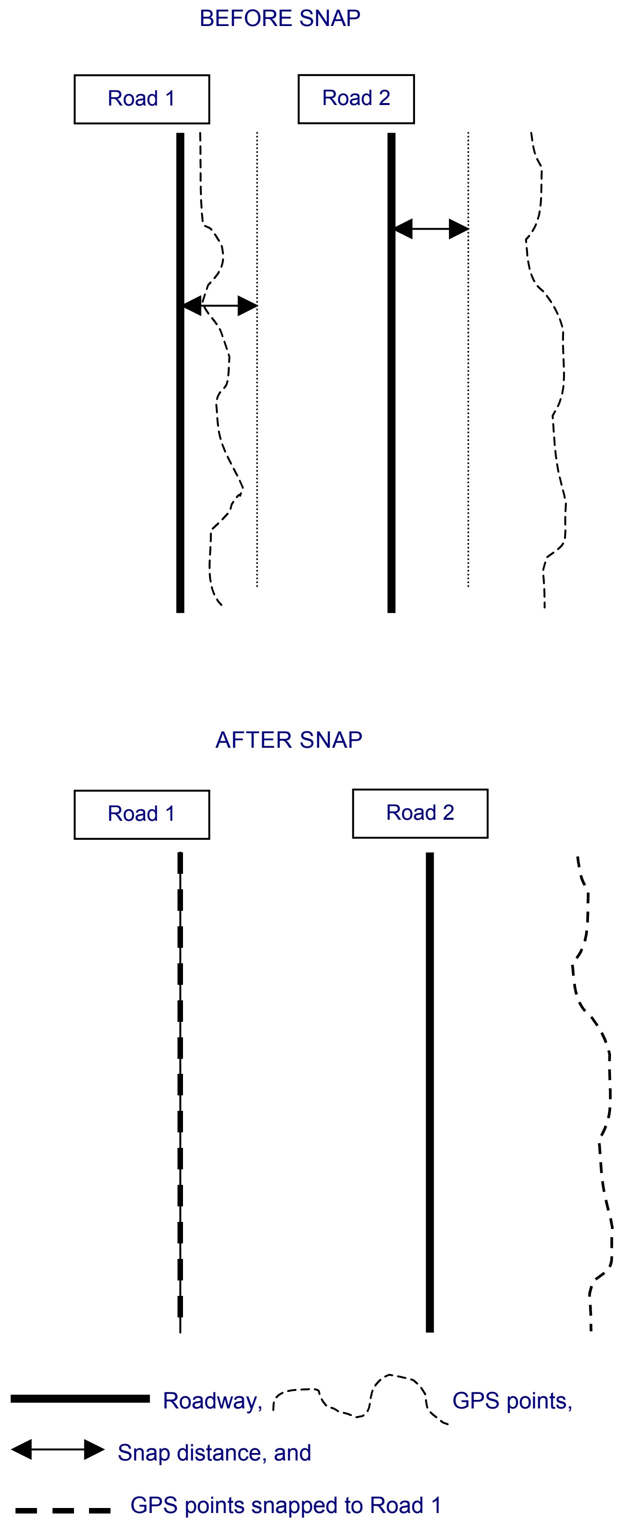

FIGURE 12 Data smoothing—Example of a snapped line.

for a given task. For example, in the previous section the problem of a stopped vehicle was identified. In the data smoothing step a rule can be established to correct the data. Doherty and others (*8*) reported that one solution to the stopped vehicle problem is the following rule:

For a five-minute stop, 60 GPS points may be located at the same place as a result of five-second GPS recording. The points will all be in close proximity to each other, with an error of between 10 and 20 meters. Detecting these stops automatically involves a rule concerning the number of points in a buffer zone of a given size around each GPS point (ignoring points that may have accumulated because of a return trip in the opposite direction). For example, the buffer could be set to 20 meters, with the number of points set to 36 (i.e., 36 × 5 seconds = 3 minutes). After a sequence of points that fit this rule is identified, the data can then be reduced such that only the first and last points in this sequence are kept. These two points then can be used to determine the start/end time of the stop and location.

The rules can become complex. Nevertheless, it is important to establish a set of rules that can be automated or applied manually to determine if data are useful. An example of an automated data smoothing technique from GIS is "snap distance." This is an algorithm that allows a data point or string of points to be moved to the closest set of adjacent points based on a maximum distance between two sets of points. Figure 12 provides an example of a snapped line of points. Roads 1 and 2 have been located using a GPS unit, but the GPS points are not congruent with the mapped roads. After the snap function is performed, the GPS points on Road 1 have moved over the mapped road. On Road 2, the GPS points did not change because they were beyond the predetermined snap distance. The user will have to decide to move them manually or re-collect the data. With the completion of data review and data smoothing, the user can proceed to the next step in the integration process map matching.

CHAPTER FIVE

MAP MATCHING

INTRODUCTION

Placing GPS data onto a base map in a GIS may produce a result in which points and arcs are not congruent. This is the classic spatial mismatch or map matching problem. Map matching results from one of four error sources.

- Accurate GIS with less accurate GPS points that do not match the GIS base map.
- Accurate GPS data placed into a less accurate GIS base map.
- Accurate GPS data placed into a GIS base map that does not have the features present to accept the GPS data.
- Accurate GPS data placed into a GIS base map that has a scale too small to differentiate the GPS points (*43*).

The major issue when trying to correct spatial mismatch or to perform map matching is to identify the approach that will provide the most accurate results with the least amount of effort while maintaining data integrity.

DETERMINISTIC MAP MATCHING

There are a variety of ways to address the map matching problem. Generally, the map matching methods are some form of pattern recognition process. The earliest map matching algorithms, deterministic models, were developed before GPS in the 1970s (*45*). The semi-deterministic method assumes an initial vehicle location on a road in the digital base map and a given direction. The algorithm then compares turns from the vehicle location to a segment of the digital base map. The algorithm must include a distance limit (10–15 m) that will indicate when the vehicle is no longer "on the road." A correction is made whenever the heading of the vehicle changes.

PROBABILISTIC MAP MATCHING

Over time, the deterministic methods evolved into probabilistic algorithms. The major advantage of the probabilistic approach is that it does not need to assume the vehicle is on the road. A vehicle heading error must be generated into a position determination. This means calculating an elliptical or rectangular confidence region (such as a probability density function) and error models within which the true vehicle location can be found. If the vehicle position within the region contains one intersection or road segment, a match is made and the coordinates on the road are used in the next position calculation. If more than one road or intersection lies within the region, connectivity checks are made to determine the most probable location of the vehicle given earlier vehicle positions. Finally, the best match segment is presented to the system along with a most probable matching point on the segment.

FUZZY LOGIC MAP MATCHING

Another potential map matching technique is fuzzy logic. It has been used by the Japanese for navigation and map matching. Although the specifics of the technique are beyond the scope of this synthesis, suffice it to say that a set of rules such as

- New heading is small, means relationship to route is high;
- Distance traveled is large, need to acquire previous segment is high; and
- Heading equals 180°, means possibility of U-turn is high

are established through which the vehicle location is determined (*46*).

PARTICLE FILTERING AND MAP MATCHING

Particle filtering, a stochastic process, is offered as another approach to the map matching problem (*47*). According to Morisue and Ikeda the "particle approximation method" can be implemented in real time and does not have any of the shortcomings of the existing deterministic methods, such as the search or statistical methods (*48*).

PERSONAL NAVIGATION ASSISTANTS AND MAP MATCHING

White et al. (*49*) discussed solutions to the map matching problem for personal navigation assistants (PNA), a piece of personal computer equipment that is rapidly gaining popularity in the United States. The PNA is considered a reasonable piece of equipment upon which to test map matching, because the PNA has a limited amount of storage space for a road network; therefore, differences between the actual position and the indicated position on the map will require interpolation on a regular basis.

The map matching problem is viewed in two ways; either as a search problem or as a statistical problem. In the context of a search problem, the goal is to match the GPS point to the "closest" node in the network. This is an easy and fast approach to implement. It depends on the way the road network was digitized into the system—with many points or few points. Many nodes are a problem because it increases file size. However, few nodes are also a problem because there are fewer nodes to which a GPS point can be matched.

White and others present the following example. Although Point *X* should be snapped to arc *A–A′*, it will be snapped to *B–B′* because it is closer to node B_1 (Figure 13).

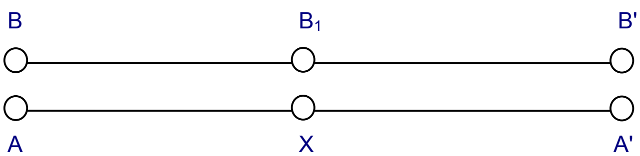

FIGURE 13 Determining a node's map match location.

The second way to view the spatial mismatch is as a statistical estimation problem. The fundamental problem is to fit a set of points to a curve where the curve is constrained to lay on the network. This approach is useful when the model describing the "physics of motion" is simple (along a straight line). In a GIS base map the motion of the vehicle is constrained by the network. This makes it difficult to model.

As they state, "In general (i.e., regardless of the metric), the curve P is closer to the curve B than it is to A (Figure 14). Thus, if one uses a simple model of motion one will be led to match P to B rather than A" (*49*).

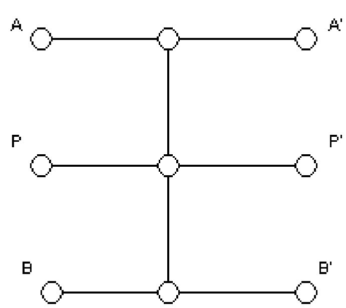

FIGURE 14 Map matching example.

White and others go on to test four algorithms that use elements of the search and statistical techniques as well as using topologic information as part of the last algorithm. Although they do not draw firm conclusions from the research, they indicate that even though algorithms 1 and 2 were used primarily as straw men to compare to the third and fourth algorithms, algorithm 2 appears to perform "the best" overall. This algorithm finds nodes that are close to a GPS point and finds the set of arcs that are incident to these nodes. It then finds the closest of these arcs and projects the GPS point onto it. Algorithm 2 also uses heading information. If the heading of the PNA is not comparable to the heading of the arc, the arc is discarded.

In addition, they identified three other points relevant to map matching. The algorithms worked better with "better" GPS points when the distances between the GPS point and the closest arc are small. Because of potential errors in the map base, this does not mean that a more accurate GPS receiver will yield better results. Second, speed plays a role. Correct matches tend to occur at greater speeds [similar to the Draijer et al. (*34*) study], because the mean speed of travel is higher on longer arcs; hence, the GPS headings tend to get better. Third, the intersection locations are the most important part of a network because most route changes occur there.

DOTS AND MAP MATCHING

Within the state DOTs a small set of techniques are used to correct map matching errors. Only four agencies have formal protocols. In place of protocols, agencies tend to use judgment and experience to determine when to adjust mismatched data. The most frequently used technique is manual corrections. As one agency indicated, "(we) mend the GIS base map to the GPS points." Two other techniques are to hold GPS points whenever possible; however, if the points are collected for presentation, then GPS points are moved (this is done for aesthetic reasons). The most frequent response to this question (24 responses) was no information provided.

The implication of the DOT responses to the spatial mismatch problem indicates that adjusting the data points is as much an art as it is a science. There is little evidence that agencies have developed formal rules or protocols for making these adjustments. Some agencies do not have digital base maps that they use consistently for projects.

The remaining three error sources and ways to address them are discussed here. In addition, a series of problems inherent to GIS that may result in problems from merging GPS data with a GIS base map are also discussed.

The second error source, matching GPS data to a less accurate digital base map, requires a determination of the type of error that exists in the GIS. Is the error systematic or random? A systematic error can be addressed with simple map adjustments. A random error may need a more complex adjustment algorithm.

One caveat on map adjustment is worth mentioning. Although map adjustments are relatively easy to accomplish in a GIS, it is also easy to reduce overall accuracy by shifting the digital base map. It has to be determined if by adjusting the map base, the overall accuracy of the map will be improved or if points are simply being matched to one another for aesthetic reasons without regard to map accuracy.

If it is assumed that the GPS data are more accurate than the map, it is appropriate to move the map. Many GIS programs accomplish this using affined or linear transformations. Affined operations use plane geometry; manipulating the coordinates themselves by scaling the axes, rotating the map, skewing the map, and/or moving the coordinate system's origin (*50*).

Two common affine map adjustment techniques used frequently in GIS to address systematic error are map shift and map rotation (Figure 15). Although the two techniques are presented separately, it is more common that they are used in combination to adjust a map. Adding scale change to shift and rotation provides the most common way to move a map to better fit data that are merged with the map base.

A shift simply means to move the position of the map some amount in the X direction and/or some amount in the Y direction. These could be equal or unequal shifts (*51*). The mathematical expression of an X and Y shift are stated as

$$X' = X + T_x \text{ and } Y' = Y + T_y$$

where

X' and Y' = the new x,y coordinates,
X and Y = the original x,y coordinates, and
T_x and T_y = the amount of shift applied to each X and Y.

Rotation is a similar concept to a shift where the map's x and y coordinates are moved through a given angle. Its equation is

$$X' = X \cos X' = X \cos\theta + Y \sin\theta \text{ and } Y' = -X \sin\theta + Y \sin\theta$$

where

X' and Y' = the new x and y coordinates,
X and Y = the original x and y coordinates,
θ = the angle to which the original coordinates will be rotated.

Another problem that occurs in map matching is random error in the map base. The congruency between the map and GPS points may be acceptable in portions of the map; however, elsewhere in the map they do not line up with arcs or nodes. One way to address this problem is through a process called conflation. One form of conflation is to use a GIS algorithm that moves internal nodes and arcs to predetermined locations within the map base. The two ways to use this technique are to allow the mapping algorithm to adjust all points on the map to a new location. This is similar to a shift and rotation. More commonly, a set of points in the map base is selected about which the remainder of the arcs and nodes will be adjusted.

An example may help to demonstrate the conflation concept. It has been determined that intersections along a corridor in the agency's map base are accurately located with a GPS unit. A regional study has been initiated and the intersections in this set do not match with GPS points from the first set of intersections. It is desirable to maintain the accuracy of the first set and improve the accuracy of the second set. By conflating the image while "tacking down" the first set of GPS points, the image will adjust about them (*2,52*). The new image may not be aesthetically pleasing, but the points will be more accurate. Only the mapmaker can determine which map characteristics should take precedence; accuracy or a map that is pleasing to view.

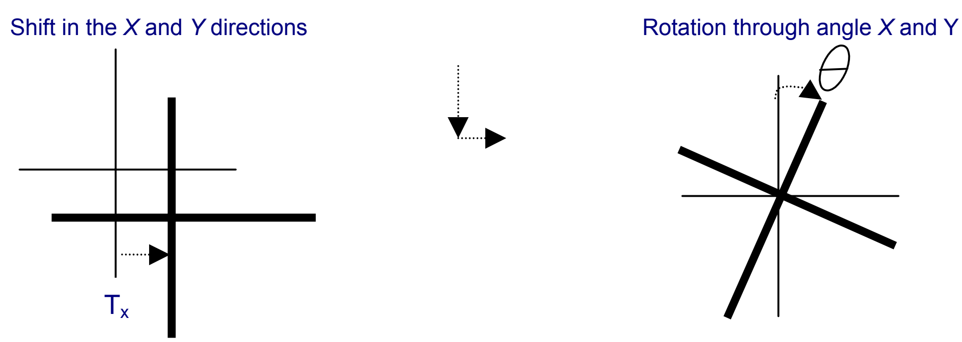

FIGURE 15 Shift and rotation as map adjustment techniques.

A variety of mathematical techniques can be used to conflate a map. Least squares is a common basis for position adjustment (*53*). In addition, quadratic expressions such as bilinear interpolation and cubic interpolation are also employed. They are considered second and third order adjustments to a map, and can cause a dramatic change in its appearance. The specific technique used depends on the level of adjustment required (*54*). Although the mathematical techniques can take a considerable time to complete, they are common in GIS and image processing software.

No amount of adjustment can provide a perfect fit between a map base and a set of GPS points. Two factors affect the goodness of fit. First, random error within the conflation calculations and the map base will introduce some level of inaccuracy. Second, numerical rounding, which occurs in any GIS algorithm, introduces error. Conflation is an excellent candidate for helping to understand the limits of a GIS to generate "perfect" results.

Although the third error source, missing data, should be identified in the data review step, the steps for correcting such data are identified here as part of the map matching process. A common example of this is trying to track a vehicle's exit from a freeway when the exit ramp has not been placed into the base map file. When data are missing, it is either an attribute accuracy problem or a currency problem. The first is corrected by searching the database to determine if an attribute has been incorrectly labeled. The problem of a map not being current is easily corrected by updating the digital base map with new information on a regular basis. Although a simple procedure, this can become time consuming and expensive if a base map is old.

A fourth error source exists when GPS data are merged into an accurate GIS base map, but the map scale is so small that the placement of the GPS points cannot be pinpointed to one street or another. This is a particularly difficult problem when working with a dense urban street network. Using a larger scale map is the solution to the scale problem. The problem occurs because the digital base map is not selected early enough in a project timeline. It may be determined that if such a base map does not exist, the project cannot be done because of the cost of creating the map. The alternative is to find the funding and create the correct map for the project. If one proceeds with a project without the proper base map, it should be expected that the results would be less than satisfactory.

With the completion of map matching, the project can proceed to the final two steps: application and improved GIS base map. Of course, the application can be completed because the project purpose drove the entire process. An improved GIS base map should be a related benefit of a project that involves map matching. The key to a quality GIS base map is to keep it current, improve the accuracy with GPS points more accurate than the base map, and maintain the metadata file for the map.

This is a large amount of work drawn out over a long period of time; however, the end product will be many times more accurate and useful than the original.

CHAPTER SIX

WIRELESS COMMUNICATION AND VEHICLE LOCATION

Although GPS has been the dominant technology used to determine vehicle locations, other technologies under the general headings of wireless communication and dead reckoning have shown potential to aid GPS and/or replace it in selected situations. This chapter explains the demand for the use of wireless communications technology and dead reckoning to aid in transportation-related positioning activities. It also identifies the variety of choices in wireless technology, as well as their current and potential uses. At the end of the chapter, there is a short summary about how DOTs currently use or plan to use wireless technology.

A number of factors have come together to generate a significant demand for wireless communication and location services. Intelligent transportation systems and smart car development have generated demand for wireless one- and two-way communication for automobiles. Automated vehicle identification and location systems are already in use. Enhanced 911 (E911) calls are commonly made to notify emergency services about accidents, while location-specific security and information services can now be provided to drivers in their cars.

The Federal Communications Commission has relied increasingly on the commercial marketplace to guide the future direction of broadcast services. ”Now a laissez-faire approach holds sway, with the marketplace determining which technology is most efficient at providing which radio service” (*55*).

There has been a rapid rate of change in wireless technology. Improvements in the size, cost, and effectiveness of the technologies have led to growth in the use of this equipment. “As the market penetration of new vehicles that are factory-equipped with wireless communications devices is poised to exceed 50% within the next five years, the potential for use of these devices as ‘traffic probes’ is substantial. That figure is projected to rise to 100% within 10 years” (*56*). However, to fully exploit the technology, the privacy of users must be maintained. Some type of encryption technology will be required to maintain privacy while still being able to obtain useful information from a wireless device.

There are two general categories of wireless technology—satellite and terrestrial. GPS is an example of satellite-based technology. A second example is low earth orbit satellites (LEO), which orbit the earth at an altitude of approximately 500 miles, compared with GPS satellites that orbit the earth at approximately 12,000 miles. According to Drane and Rizos in 1998, seven different LEO systems were either in place or in the planning stages. They state that

> More dramatic will be the changes in the space segment, where the number of non-GPS satellites transmitting GPS-like signals might significantly outnumber the official GPS constellation! These additional signal-transmitters will mostly be of the low-earth orbiting variety, whose main function will be to support mobile satellite communication and data transfer. Eventually, ITS satellite-base positioning services might be exclusively provided by these non-GPS satellites as a by-product of their communication function (*57*).

The other major categories of positioning systems are earth-based systems including dead reckoning and wireless cellular communication. Dead reckoning, which is also known as inertial navigation, is one of the oldest forms of positioning; however, it has been updated to use modern technologies such as gyroscopes and accelerometers to provide vehicle position data. It can be used to supplement or even replace GPS data.

Wireless communication is actually composed of 15–20 different types of related wireless phone technologies. The most common phone technologies that are relevant to transportation applications include analog and digital cellular telephony, personal communication services (PCS), and radio paging.

Analog service has been available for many years. For example, United Parcel Service has made use of it to transmit tracking data from its delivery vehicles. However, analog service was not meant to transfer large amounts of data; it does not perform as well as modern packet systems. Its coverage area is also limited.

Digital cellular service is expanding rapidly across the United States. Unlike analog service, digital cellular can send data without interruption. One problem that digital services face is the lack of a nationwide digital standard. If a vehicle carries a unit with one standard and the vehicle enters an area using a different standard, the unit typically will not function. In addition, digital cellular services have a difficult time sending and receiving signals in mountainous terrain or anywhere a signal shadow exists (i.e., places where signals are physically blocked).

In England, cellular phones have shown the potential to provide origin and destination data by recording the beginning and ending locations of a phone call. This information is

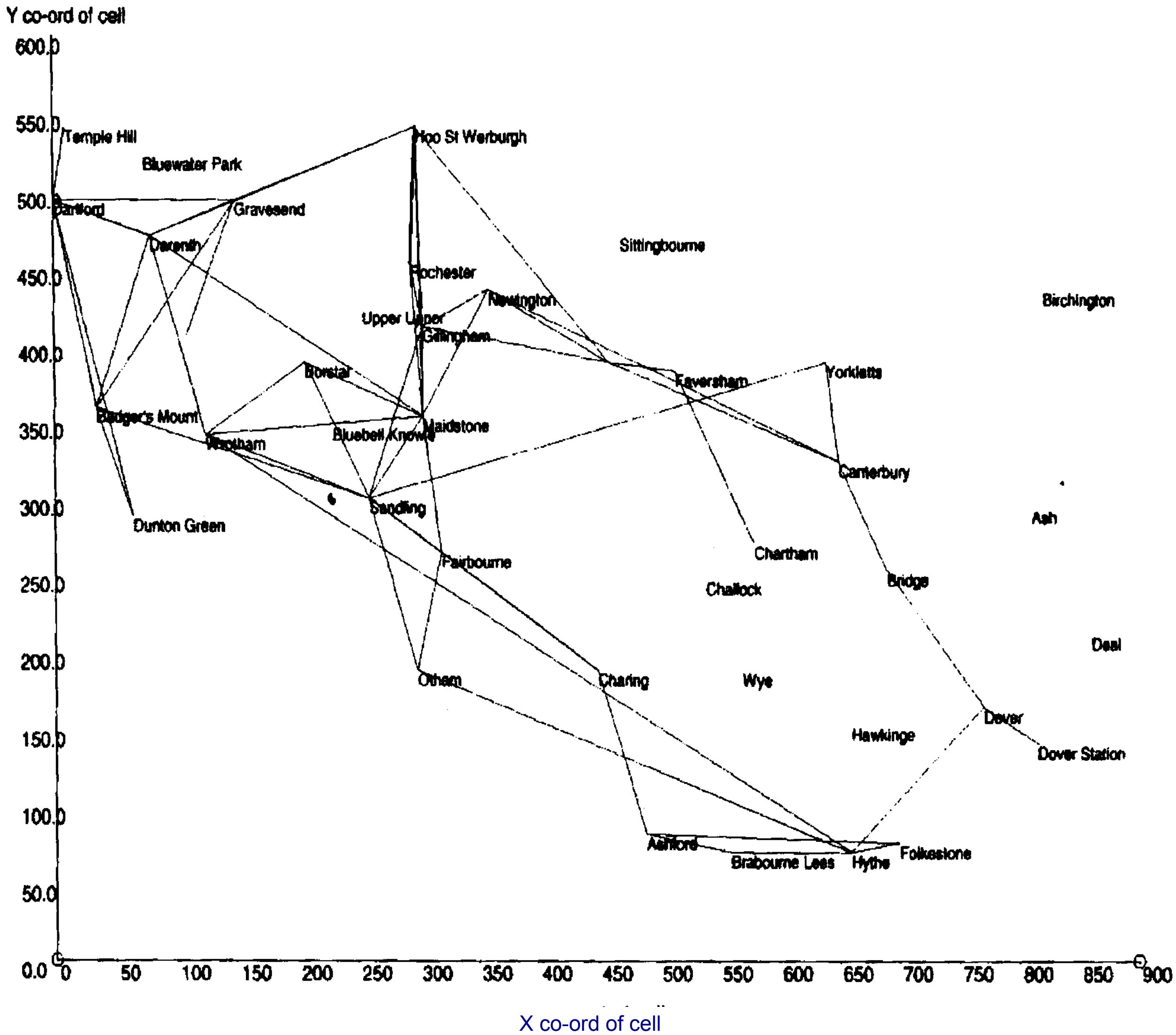

FIGURE 16 Origin–destination matrix from Kent, England, billing area data [source: White (*58*)].

obtained by identification of the cell tower nearest the first and last signal from the phone. In addition, these "origin" and "destination" locations are also noted in the billing record of users (Figure 16). Although one user's record is of little use, thousands of records can provide significant information about a population's travel behavior (*58*).

Another technology with promise is PCS. The PCS operate on lower power levels than either analog or digital cellular telephone. Equipment is lighter, smaller, and can operate longer on a single charge. Like other wireless technologies, PCS is generally limited to urban and suburban areas.

Each of the terrestrial systems operates with towers equipped with antennas to send or regenerate a signal. If the demand for service is high, the number of towers is high. This means that in the most congested urban areas, the density of cell towers that can be used for positioning is high. However, unlike GPS satellites that are placed in a configuration in space to work with one another as navigation tools, towers are placed to work as independent units. If two towers are visible from a given location, it is generally considered poor engineering because their service areas probably overlap. The stand-alone nature of towers makes them less than ideal as tools for navigation or positioning. It may be that in some cases additional towers will be required to increase the accuracy of terrestrial positioning to meet location accuracy requirements. Even with these limitations, it has been demonstrated that wireless communication can be used to calculate positioning data especially when used in conjunction with GPS. Wermuth and others indicate that even though the Global System for Mobile Communication depends on the density of towers and cannot reach the accuracy of the GPS technique, it is

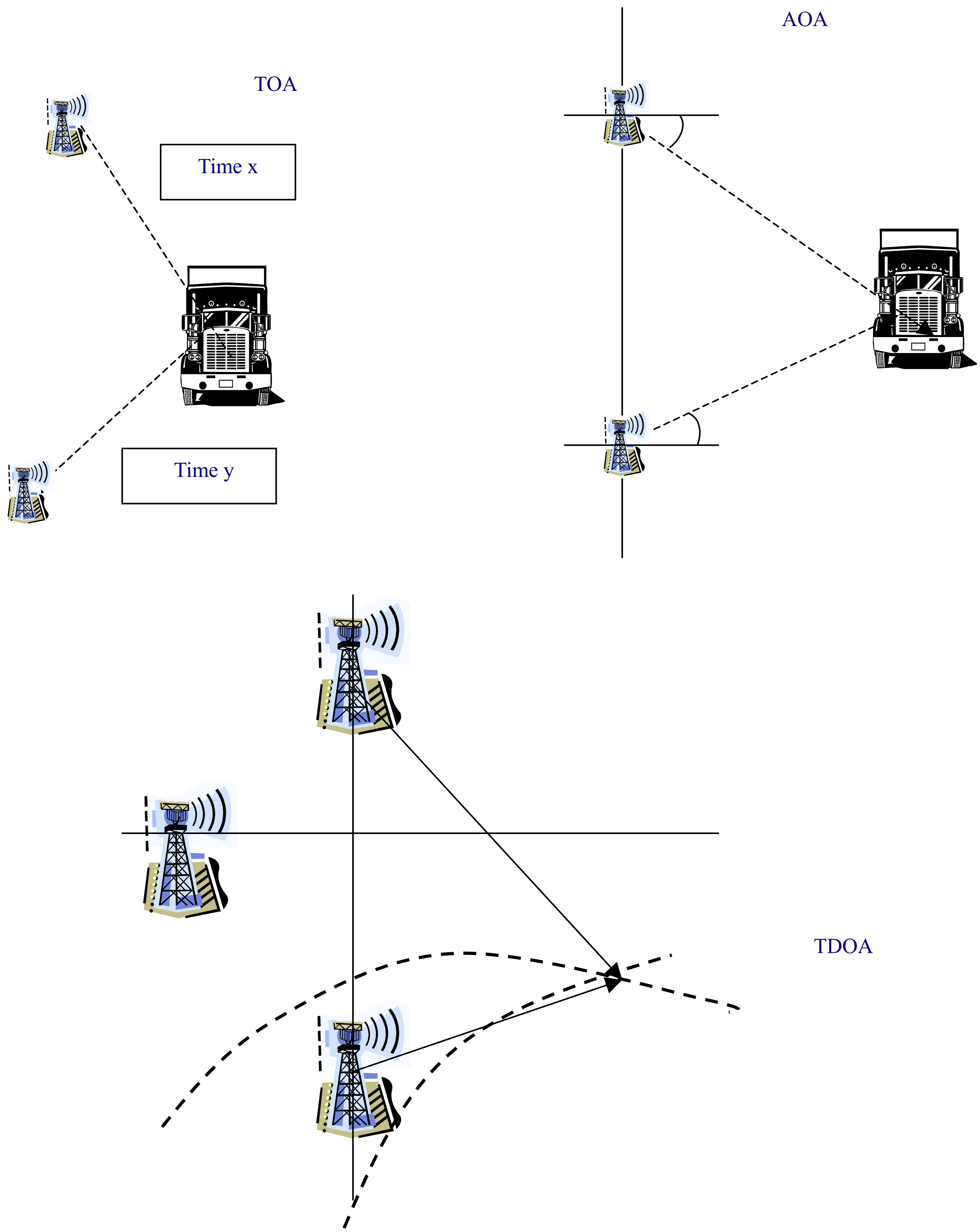

FIGURE 17 Vehicle location methods from wireless tower and time.

generally adequate (50–100 m) for purposes of long-distance travel surveys. In addition, they state that algorithms can be used to raise the accuracy (*59*).

Because the speed at which wireless communication signals are received or sent is generally considered fixed, in most cases at the speed of light, the time needed to send a signal from a vehicle to a tower can be used as a measure of distance. If a vehicle's signal is received at a minimum of two towers simultaneously, it can be used to determine the vehicle's location via triangulation. The federal government originally required wireless phone operators, through its FCC E911 Phase 2 mandate, to deploy location technology into their networks by October 1, 2001 (*60*). The original deadline has been altered so that by December 31, 2002, 100 percent of all newly activated digital handsets will be capable of automatic location identification. For emergencies, all mobile phone companies are required to locate mobile phones to the nearest 125 m, 67 percent of the time (*58*).

There are three terrestrial-based wireless methods for determining a vehicle location (*13*): angle of arrival (AOA), time of arrival (TOA), and time difference of arrival (TDOA) (Figure 17). The AOA technique uses radio frequency triangulation to determine a vehicle's position. By calculating the angle of incidence for two towers, the position of the vehicle can be determined. The positive aspects of AOA include the need for only two towers. In addition, there is no need to maintain synchronized signals as in TDOA. The negative aspects of this technology include susceptibility to signal blockage and multipath error.

TOA measures the propagation time of signals broadcast from multiple transmitters at known locations to determine a vehicle's location. This is the same technology as GPS except that towers and transmitters take the place of the GPS satellites.

The last technique, TDOA, uses a time synchronized radio signal that is broadcast from known transmitter locations (or from the vehicle to the towers). The differences among the path lengths can be measured by the time differences of the signals between the towers and the vehicle. The calculated vehicle position can be determined by the time difference pairs at the intersection of two hyperbolas. The major drawback of TDOA is the need to maintain the synchronized signals among all transmitting towers. GPS could be used in combination with TDOA to address the time synchronization problem. These technologies have been labeled Network Assisted GPS or A-GPS.

A-GPS location technology uses GPS positioning in a vehicle with the addition of fixed GPS receivers or transmitters placed at regular intervals. The data from the fixed stations make it possible for the in-vehicle GPS receiver to make timing measurements. This greatly reduces the time it takes the GPS unit to calculate its position. Without assistance, it can take from 20 s to more than 1 min to Time-to-First-Fix (TTFF). With A-GPS, the amount of time required to obtain TTFF can be reduced to less than 10 s (*60*).

This is important for two reasons. First, it shows that GPS can be supplemented with other technologies. An example of where the A-GPS and TTFF features are useful is in urban canyons where GPS could easily lose the lock on a satellite. For navigation purposes, A-GPS can dramatically reduce the time to reacquire the satellites and restore the link to the GPS units. Furthermore, the interference of GPS signals from buildings in a large CBD may be so consistent that the terrestrial-based system may have to supplant the location function of the GPS for an extended time.

The second terrestrial category of positioning data is inertial navigation or dead reckoning. This type of technology is useful because of problems with GPS such as multipath, shadowing, signal loss, and dynamic jerk (rate of change of acceleration). They may create two outcomes: (1) the GPS unit does not provide any position information (or repeats its last location) or (2) the position accuracy is severely degraded. As a result, inertial navigation can supplement GPS positioning or in some cases replace it. This may be especially true in places where the "urban canyon" effect is severe; that is, New York City, Chicago, or San Francisco.

Dead reckoning is one of the oldest navigation and positioning techniques. The two essential data elements for dead reckoning are a tool that provides a heading (mariners used compasses) and a velocity or distance indicator. In place of the compass, vehicles can use a gyroscope, accelerometer, or a two-wheel odometer (*61*). The gyroscope is a proven technology for heading data; it has been used in airplanes for this purpose. The odometer is the distance or velocity indicator.

Both the gyroscope and odometer contain error sources. To obtain accurate position information, these error sources must be addressed. Because of gyroscope bias and other error sources, it requires frequent heading recalibration. The odometer may also require calibration because of wheel slip or changing ratios between axles and tire size (*60*). This can be provided by a GPS unit working in combination with the dead reckoning technology. In Adelaide, South Australia, a GPS dead reckoning-assisted unit was tested in comparison to a GPS stand-alone unit (*62*).

In Adelaide's CBD, where urban canyons exist, the GPS unit lost contact with satellites or could only maintain communication with one satellite, and the positioning track wandered, whereas the GPS dead reckoning-assisted unit was able to maintain a constant, accurate vehicle position. Even in a 500-m tunnel, the GPS dead reckoning unit was able to retain the vehicle track and then reacquire the GPS signal upon exiting the tunnel.

The Internet can transmit positioning data collected by GPS or other sources to a vehicle using digital cellular or PCS. An experiment in Japan has demonstrated the potential usefulness of the Internet to provide location data and to enhance GPS data with correction information. It can provide either DGPS or mobile GPS correction information to the GPS unit. It should be noted that a 24-channel GPS/GLONASS (Global Navigation Satellite System) receiver and an in-vehicle personal computer were used during this experiment. Although this was only experimental, it demonstrated the ability of the GPS to be integrated with wireless technology and the Internet to increase GPS accuracy (*63*).

Of the 46 responses to the survey questionnaire, only 5 mentioned wireless communication as an option. One response indicated the agency used wireless technology for real-time differential correction. A second DOT also mentioned that real-time DGPS was transmitted for road centerlines using wireless communication. Two other responses indicated that it was possible that the agency might use the technology within the next 3 years. The fifth response noted that the agency was aware of the option to use wireless technology, but there were no plans to use it within the next 3 years. None of the remaining 41 responses mentioned the wireless option.

The final question in the survey asked whether the agency was planning to use cellular technology for location purposes within the next 3 years. Six potential uses were identified.

- Calculating traffic speed,
- Congestion monitoring,
- Mass data collection,
- Mobile GPS positioning,
- Traffic management, and
- Tracking vehicles.

Thirty-six respondents specified that either there are no plans to use wireless technologies or they did not respond to the question. It appears that this is a new idea to most agencies. At this time, they are only thinking about how cellular technology might be used. For most agencies, it is not a viable option any time in the near future.

CHAPTER SEVEN

CONCLUSIONS

The integration of GPS and GIS is an exciting and challenging combination of technologies. It offers the potential of more and better spatial information for transportation planning, decision making, and research. This spatial information will be obtained at higher levels of accuracy and at lower costs than any other combination of positioning and mapping information available to state departments of transportation (DOTs) and metropolitan planning organizations. As GPS and GIS are integrated to achieve the technologies' potential, some guidelines should be given serious consideration. A sample set of guidelines, based on the six-step process detailed in this synthesis, is outlined in Appendix E. In addition, some general ideas about GPS and GIS integration have been identified.

First, everyone must be aware of the project purpose. This drives the selection of map projection, scale, and datum and predetermines the characteristics of the spatial attributes presented in the base map. It also drives the second step, data collection. Ignoring project purpose in the data collection step inevitably increases the time to collect (and re-collect) data that can increase project cost. Therefore, it is not surprising that the data collection step contains the largest number of guidelines (Appendix E). The implication is clear; to obtain accurate and useable GPS data, one must preplan, train data collectors, and use clear and specific written rules for data collection.

Third, in the data review and smoothing step, one must identify the data that are essential to achieving the project purpose. This means eliminating bad, extraneous, or duplicate data and adding or replacing missing data. To accomplish this, agency-specified spatial thresholds must be established indicating when these actions are appropriate. In this way, a project maintains spatial consistency over time.

With the completion of data review and smoothing, the fourth step, map matching, may be undertaken. By definition, all remaining GPS data are acceptable and the digital map is accurate and current. All GPS data fall within some predetermined threshold relative to the base map. If the GPS points and base map are not congruent, it may be straightforward to use a "snap function" to match the GPS points to the base map. If the error is random, there may be a need to manually move points. This appears to be the most common technique among state DOTs. In addition, there may be smoothing algorithms in the GPS post-processing software that can help to correct this problem. It may also be necessary to conflate the map to bring it in line with the more accurate GPS points. This is a drastic step and may reduce the spatial accuracy, as well as distort the aesthetics of the map. The distortion can be so severe as to make the map appear unrealistic.

If the first four steps are completed using the guidelines, as well as standard GPS data collection procedures and standard cartographic techniques for data representation, the fifth step, application and output, should be achieved to a satisfactory level. The sixth and final step, data maintenance and improving the GIS base map, is often forgotten or completed in a haphazard manner. Data should be saved and stored so that it may be retrieved later. There is no doubt that if a project gathers accurate GPS positional data, these data should be used to upgrade a less accurate GIS base map. In addition, any corrections, additions, and/or deletions to the base map should be undertaken at the same time. It cannot be stressed enough that over the long term maintaining a current and accurate base map (or set of base maps at different scales) is a cost-saving mechanism.

Finally, all digital maps should have their associated metadata tagged to them. This is essential for the long-term usefulness and transferability of a digital map and its associated database. It may take many years to build a better digital map, but using accurate GPS points from a variety of projects can result in a digital base map that possesses a higher level of spatial accuracy. This will make map matching less of an issue.

Mapping activities in state DOTs employ a broad range of spatial accuracy, whereas surveying requires a much higher level of accuracy. It may be that if transportation planners and engineers want more information from travel surveys, they will have to migrate toward more accurate and more expensive GPS data collection processes. The trade-off between more accurate and more complete data versus the cost of a project is nothing new; it is an issue that all agencies must face. GPS data collection and processing and GIS construction are becoming less expensive. In the near future, we will have more positioning alternatives as wireless and dead reckoning positioning devices supplement or replace GPS. These factors, combined with the field application of the conceptual work done by a variety of researchers presented in the synthesis, will generate more and better spatial information for transportation planning, engineering, and research.

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GLOSSARY

Integrating GPS and GIS data borrows terminology from a variety of disciplines including surveying, geography, geodesy, and mathematics. Information for this glossary was excerpted from various references including *The Global Positioning System, Fundamentals of GIS, Datums and Map Projections, and Elements of Cartography.*

Automated Vehicle Identification—A vehicle's position (latitude and longitude) identified by GPS or wireless communication technology. The position is used to locate the vehicle or to track its path.

Blockage—GPS signals that are stopped before reaching the GPS receiver. This is usually caused by a physical object, such as a building or a heavy vegetation canopy. Blockage is most common in the central business districts of cities where tall building stop GPS signals.

Conflation—The general objective of conflation is to combine two digital maps into one and to reconcile the best features geometries and their related attributes from the two maps. Points from one map are adjusted to fit the positions of the points on the second map. It is usually assumed that the points on the second map are more accurately positioned than the points on the first. Although the term "rubber sheeting" implies forcing points to fit another set of map points, the process is actually more complicated than just moving points.

Datum—A mathematical model that is designed to provide the best fit for all or part of a selected geoid. It is defined by an ellipsoid and the relationship between the ellipsoid and a point on the topographic surface established as the origin of datum.

Differential Global Positioning System (DGPS)—A technique used to improve positioning or navigation accuracy by determining the positioning error at a known location and subsequently incorporating a corrective factor (by real-time transmission of corrections or by post-processing) into the position calculations of another receiver operating in the same area and simultaneously tracking the same satellites.

Dilution of Precision (DOP)—A description of the geometrical contribution to the uncertainty in a position. Standard terms for GPS application are GDOP, Geometric (three position coordinates plus clock offset in the solution); PDOP, Position (three coordinates); HDOP, Horizontal (two horizontal coordinates); VDOP, Vertical (height only); TDOP, Time (clock offset only); RDOP, Relative (normalized to 60 seconds).

Geocode—A location in geographic space converted into computer-readable form. This usually means creating a digital record of the point's coordinates or street address.

Global Navigation Satellite System (GLOSNASS)—A GPS system developed by the Russian Federation. With special equipment, U.S. mappers and surveyors can increase the number of satellites available for positioning by using the Russian system.

Map Matching—A variety of methods used to bring together two sets of map points. The example used most frequently within the synthesis is aligning GPS points with a GIS digital base map.

Multipath—GPS signal interference caused by the signals arriving at the GPS receiver after unintentionally being reflected from the surfaces of objects located between the satellite and GPS receiver. Typically, GPS signals are reflected from nearby structures or other reflective surfaces. Signals traveling longer paths produce higher (erroneous) pseudo-range estimates and, consequently, positioning errors.

Precise Positioning Code (PPS)—The most accurate positioning possible with GPS, based on the dual frequency P-code. A very long sequence of pseudo-random binary biphase modulations on the GPS carrier. Each 1-week segment of the PPS is unique to one GPS satellite and is reset each week. This service is limited to authorized U.S. and allied federal governments, authorized foreign and military users, and eligible civilian users. PPS information is usually (but not always) encrypted to prevent use by unauthorized users.

Projection—Presenting data from a spherical surface (the Earth) on a flat surface (computer screen, sheet of paper, or Mylar or other flat media). The most common projection used by state departments of transportation is the Transverse Mercator projection sometimes identified as the Universal Transverse Mercator projection. This "conformal projection," where angles are correctly represented, is ideal for presentation of a topographic map where latitude and longitude or any grid system can be represented at right angles. Simply by changing projection, a task easily accomplished in GIS, the position, shape, or direction on a map can be altered. Using different projections often results in map matching problems.

Real-Time Kinematic (RTK) GPS—RTK is currently carrier phase observations processed (corrected) in real-time resulting in position coordinates to a 1–2 cm accuracy level being available to the surveyor in the field. RTK consists of two or more GPS receivers, three or more radio modems, and a handheld survey computerized data collector. One receiver occupies a known reference station and broadcasts a correction message to one or more roving receivers. The roving receivers process the information to produce an accurate position relative to the reference station.

Selective Availability (SA)—An intentional degradation of the full SPS code capability. When SA is activated, it degrades the SPS code positioning capability to 100 m.

Standard Positioning Service (SPS)—Also referred to as the C/A code (coarse acquisition or clear/access), the standard GPS code is a sequence of 1,023 pseudo-random binary biphase transitions of the GPS carrier that has a code repetition period of 1 millisecond. The SPS is intended for general use and is capable of providing instantaneous point position navigation accuracy at the 30-m accuracy with SA deactivated.

Topologically Integrated Geographically Encoded Reference Line Files (TIGER)—Digital map files developed by the U.S. Census Bureau to aid in collecting and analyzing census data. TIGER files were used in the 1990 and 2000 census. Although the digital files have a comprehensive set of information in them including roads, boundaries, labels, and census geography, their accuracy is limited. This is the case because map accuracy is not critical to the successful collection of census data.

Urban Canyon Problem—Inaccurate GPS position coordinates are generated when the GPS signal is blocked or bounced off buildings in a highly urbanized location. This usually occurs in the central business district of cities. Numerous tall buildings prevent continuously accurate GPS positions from being generated.

APPENDIX A

Questionnaire

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
Project 20-5, Topic 31-05

Performance Measures for Research, Development, and Technology Programs Data into a Geographic Information System

Questionnaire

This questionnaire is being mailed to you as part of a TRB synthesis study. The general topic for the synthesis is the use of the global positioning system (GPS) and a geographic information system (GIS) as tools in transportation planning. The focus of the project is how kinematic or dynamic GPS data collection is integrated into GIS systems. Kinematic GPS data collection is used in such applications as fleet monitoring analysis, travel surveys, and speed studies. Specifically, we are trying to determine how dynamic GPS data points are collected, processed, and placed into GIS systems. If you have collected dynamic GPS points and placed them into a GIS, we would be most interested in your response to the questionnaire. If you have not used the technology for this purpose, we still need to know if you have policies, procedures, and/or guidelines that influence the integration of GPS data into your GIS system. One of the questions that must be addressed in the synthesis is whether agencies and firms treat static and dynamic data differently. We can only determine this if we have information about both types of data.

The questionnaire addresses three related topics: 1) how GPS data are collected, 2) how GPS data are processed to work with a GIS, and 3) how GPS data are integrated with a GIS. The project is particularly concerned about standards, protocols, and/or administrative policies that have been developed to protect the quality and integrity of kinematic data and associated data products. In addition we are also interested in case studies that may demonstrate how GPS has been used within a GIS context for transportation projects that involve kinematic data. However, if you have not undertaken this type of study, we still want to know the process used in projects involving your GPS data.

Please return your completed questionnaire, along with any supporting documents, by **July 14, 2000** to:

Robert J. Czerniak, Ph.D.
New Mexico State University
Department of Geography
Breland Hall, Room 107
PO Box MAP
Las Cruces, NM 88003-30001

If you have any questions please contact Professor Czerniak by phone on (505) 646-2815, by FAX on (505) 646-7430, or by e-mail at rczernia@nmsu.edu.

SECTION 1 BACKGROUND

Below, please provide the name of the person completing this questionnaire and/or someone else who may be contacted to obtain any needed follow-up information:

NAME____

TITLE____

AGENCY____

STREET ADDRESS____

TOWN/STATE/ZIP____

TELEPHONE____

FAX____

E-MAIL____

As you answer questions on the following pages, please feel free to add pages or write on the back of the questionnaire. Any documentation on standards, protocols, guidelines or case studies you provide, will be greatly appreciated.

THANK YOU VERY MUCH FOR YOUR HELP

SECTION 2 DATA COLLECTION

The synthesis will provide information about how agencies collect kinematic GPS data. Of particular interest is how data quality is maintained and whether formal or informal procedures are used to maintain data quality.

1. How long has your agency employed GIS? __________ years

2. How long has your agency employed GPS? __________ years

3. Have you used GPS for any of the following applications (Provide examples when appropriate)?

Locating points (Level of spatial accuracy required or desired)

Example 1____________________ (kinematic) _________________________

Example 2 ____________________ (static) _________________________

Example 3 ____________________ _________________________

Locating arcs

Example 1____________________ (kinematic) _________________________

Example 2 ____________________ (static) _________________________

Example 3 ____________________ _________________________

Locating areas or polygons

Example 1_____________________ _________________________

Example 2 ____________________ _________________________

Example 3 ____________________ _________________________

4. Do you have formal protocols or written methods for the collection of kinematic or static GPS data? (only check one box below). For example, do you require that the data be collected using real-time differential GPS corrections from a base station or a satellite?

   ❑ No, if no, please go to question 5.
   ❑ Yes, for kinematic data (if yes, please provide the written documentation)

   What level of spatial accuracy do you require? (Check one)

   Submeter______ 1–2 meters_______ 3–5 meters______ More than 5 meters______

   Yes, for static data (if yes, please provide the written documentation)

   What level of spatial accuracy do you require? (Check one)

   Submeter______ 1–2 meters_______ 3–5 meters______ More than 5 meters______

5. Do you use informal (verbal or experiential) rules for collecting GPS data? (Only check one box below)

- ❑ Yes, for kinematic data, please list them below
- ❑ Yes, for static data, please list them below
- ❑ No, please go to question 6.

Please list the three most important informal rules for collecting GPS data.

1. ______________________________
2. ______________________________
3. ______________________________

6. Have you borrowed methods or rules for collecting GPS data from other agencies, companies, educational institutions, or professional societies? Please provide the three most important rules you have used. If do you not use outside methods or rules, go to question 7.

(3 maximum).

1. ______________________________
2. ______________________________
3. ______________________________

7. Are you required to use accuracy (meaning freedom from systematic bias) standards for your GPS data collection? (Only check one box below)

- ❑ Yes, for kinematic data, go to question 8
- ❑ Yes, for static data, go to question 8
- ❑ No, go to question 10.

8. Are the standards generated from within the agency?

- ❑ Yes, please provide a copy of the standards
- ❑ No, please go to question 9.

9. What is the external source of your GPS accuracy standards? (Check all that are appropriate)

- ❑ State Statute (please provide a copy of the relevant statute)
- ❑ Professional Society (please provide the name below)

Society name______________________________

- ❑ National Map Accuracy Standards
- ❑ National Standard for Spatial Data Accuracy
- ❑ Spatial Data Transfer Standards
- ❑ National Imagery and Mapping Agency Standards
- ❑ Other______________________________

SECTION 3 DATA PROCESSING

The synthesis study is concerned about how you process or manipulate GPS data after it has been collected. The focus is on the processes and algorithms that are used to accomplish this task.

10. If you use a standard map projection, what is the standard projection that you use? If you do not use a standard projection, go to question 11.

❑ UTM
❑ Geographic or geodetic (actually a non-projection)
❑ Albers
❑ Other____

11. If you use a standard datum, which datum do you use? (Please check the most frequently used items). If you do not use a standard datum, go to question 12.

❑ NAD 1927
❑ NAD 1983, 1986 adjusted
❑ NGVD 29
❑ NAVD 88
❑ Ellipsoid Heights
❑ Other____

12. In addition or in place of a projection do you convert GPS data into other coordinate systems?

❑ State Plane ❑ Other____
❑ Local system (County, city, etc.)

Most frequently used local coordinate systems (two maximum)

1. ____

2. ____

13. Do you have a standard for eliminating "bad" kinematic GPS points? If you do not collect kinematic data, please list the standards for the elimination of "bad" static GPS data. Please provide a copy of the standards or write the policy below.

14. For mapping purposes, do you ever use uncorrected GPS data?

If yes, what is the most common application?

____

No, please go to question 17.

15. Do you use real-time differentially corrected GPS?

If yes, what is the most common application?

____

No, please go to question 18.

16. Do you post-process GPS data?

    If yes, what software do you use to process kinematic data?

    ____

    If yes, what software do you use to process static data?

    ____

    If no, go to question 20.

17. What tasks does the post-processing accomplish for you? (Check as many as apply)

    ❑ Provides calculated average location for a given point
    ❑ Drops bad data points
    ❑ Identifies bad data points for manual deletion
    ❑ Smoothes data points
    ❑ Other____

18. If your agency has internal protocols or formal methods for data processing, please provide the documentation for them.

19. If your agency uses external protocols and/or formal methods for data processing, please provide the name of the external source(s).

20. If you do not use written protocols or formal methods, are there unwritten rules for data processing? Please list the three most important rules, protocols, or methods.

    1. ____

    2. ____

    3. ____

21. If you use specific algorithms to process kinematic GPS data, please list the three most important ones below. If you do not process kinematic data, but use specific algorithms for static data, list them.

    1. ____

    2. ____

    3. ____

    If you have references for the algorithms, please provide them or copies of appropriate pages.

SECTION 4 GPS/GIS INTEGRATION

The synthesis will discuss how agencies mix and match GPS and GIS data layers. The central issue is how to register GPS data with other data layers. This is also called the "spatial mismatch" or "map matching" problem. This section asks you to identify problems associated with this process and methods used to mitigate any identified problems.

22. Does your department or agency have a digital base map? (Check one)

   ❑ Yes, please go to question 23
   ❑ No, please go to question 32

23. Is there any effort in your agency to integrate the digital base map and GPS? (Check one)

   ❑ 1. Yes, we integrate kinematic data with the base map, please go to question 24.
   ❑ 2. Yes, we integrate static data with the base map, please go to question 24.

   Note: If you respond to this question checking #1, respond to questions 27–34 in terms of your kinematic applications; if you respond to #2, respond in terms of your static applications.

24. Have you experienced problems with the integration of GPS data into GIS layers?

   ❑ Yes, please go to question 25.
   ❑ No, please go to question 32.

25. List the three most common problems you have experienced when attempting to place GPS data into a GIS base layer.

   1. ______________________________
   2. ______________________________
   3. ______________________________

26. How do you resolve the conflict between the locations of GPS data and the different locations of the same data within a GIS base layer?

27. Do you use a formal protocol for adjusting spatial mismatches between GPS data and a base layer in your GIS?

   ❑ Yes, please go to question 28.
   ❑ No, please go to question 32.

28. What level of spatial mismatch do you allow between points before you undertake an adjustment?

   For individual points______________________________

   For arcs______________________________

29. If different mismatch distances are used for different scales, please provide documentation to indicate the allowed distances by scale.

30. What is the source(s) of your mismatch standards?

31. What specific algorithms do you use to correct spatial mismatches (points, arcs, or polygons) of data points?

    1. ______________________________

    2. ______________________________

    3. ______________________________

    If you have references for these algorithms, please provide them.

32. Does your agency use metadata for data it creates?

    ❑ Yes, go to question 33.
    ❑ No, go to question 36.

33. What standard do you follow in the preparation of your metadata. If you have documentation for it, please include it in the packet that you return with the questionnaire.

34. Does your agency use data from other sources that do not have metadata tied to it?

    ❑ Yes, go to question 35.
    ❑ No, go to question 36.

35. How do you verify the accuracy of data if they do not have metadata associated with them?

36. If your agency has used or plans to use (within the next 3 years) cellular technology for any spatial position measurements, please list them below.

    1. ______________________________

    2. ______________________________

    3. ______________________________

37. Case studies and innovative applications of kinematic GPS data collection, processing, and GIS integration are important to the synthesis. If you know of any written case studies or innovative applications that were not addressed in earlier questions, please provide documentation or describe them on the back of this page as necessary. If you would like to talk about your case study please indicate that here as well and you will be contacted.

THANK YOU AGAIN FOR YOUR HELP IN PROVIDING INFORMATION FOR THE SYNTHESIS!

APPENDIX B

Survey Results

DATA COLLECTION—BACKGROUND

Agency	GIS (yrs)	GPS (yrs)	Surveying	Control	Marker/Sign Location	Capturing Road Data	Other
AK DOT	8	4				x	Structures
AZ DOT	9	2			x		
CATS	7	0					
CT DOT 1	9	0					
CT DOT 2	5	8					
CT DOT 3	5	5					Photolog
CT DOT 4	0	8				x	
DE DOT	0	4		x			
FL DOT	7	5				x	
GA DOT	7	4				x	
GA DOT IT Div	7	1				x	Traffic recording system
HI DOT	0	1	x	x			
KPMG	10	10					
KS DOT	15	8		x			Videolog, pavement management
KY Trans	10	1				x	
LA DOT	14	10	x	x		x	
MD DOT 1	10	10					Soil boring, storm drains, traffic monitoring
MD DOT 2	0	10	x				Wetlands inventory
ME DOT	7	5					
Metro Wash COG	10	3					Velocity measurements
MI DOT	15	4			x		Bridge location
MS DOT	4	1	x				
MT DOT	18	5			x		Stockpile locations
MTC	0	0					Call box location
ND DOT	7	7			x	x	
NE Road Dept.	10	6				x	
NH DOT	13	13		x		x	Well location
NYS DOT	5	6		x	x		Airborne GPS, well location
OK DOT	6	5	x			x	
OR DOT	10	5	x	x			Rockslides, storm water outfills
PA DOT	10	2					
SEMCOG	8	2					Bus stop locations
St. Cloud Area Plan	8	0					
TN DOT	8	14	x			x	
UT DOT	3	1			x		Photolog
WA DOT 1	0	0		x			
WA DOT 2	0	5					Storm water outfills
WA DOT 3	10	0				x	
WA DOT 4	5	14		x			
WA DOT 5	0	3					Feature points
Wasatch Fron Reg C	0	2				x	
WVA DOT	0	0					
WY DOT	2	0					

DATA COLLECTION—ACCURACY

Agency	Survey	Control	Marker/ Sign	Road Data	Line Applications	Line Accuracy	Polygon Applications	Polygon Accuracy
AK DOT							City limit delineation	
AZ DOT			5 Meters		Road centerline	3 to 5 Meters		
CATS								
CT DOT 1								
CT DOT 2								
CT DOT 3								
CT DOT 4				NA				
DE DOT		Submeter						
FL DOT				± 5 Meters				
GA DOT				± 5 Meters	Road centerline	5 Meters		
GA DOT IT Div				± 20 Meters	Road centerline	5 Meters		
HI DOT		Submeter						
KPMG								
KS DOT		Unknown			Videolog			
KY Trans				Submeter	Road centerline	Submeter		
LA DOT		Order B		Submeter				
MD DOT 1					Road inventory	1 to 3 Meters	Reforestation, wetland delineation, storm water facilities	Submeter to 5 Meters
MD DOT 2	1 Meter							
ME DOT								
Metro Wash COG					Velocity and time measurements			
MI DOT			1 to 2 Meters		Road centerline	1 to 3 Meters	Wetland delineation	2 to 5 Meters
MS DOT	Submeter				Road alignment	3–5 Meters		
MT DOT			± 20 Meters		Road centerline	5 Meters		
MTC								
ND DOT			Submeter	Submeter	Road centerline	Submeter	Wetland delineation Gravel pits	Submeter
NE Road Dept.				± 1.5 Meters @ 60 mph	Road centerline	± 1.5 Meters @ 60 mph		
NH DOT		Submeter		3 to 5 Meters	Road centerlines, railroads, utilities	3 to 5 Meters	Wetlands	
NYS DOT		Submeter	5 Meters		Wetland delineation	1 Meter	Wetland delineation	1 Meter
OK DOT	Submeter			3 Meters				
OR DOT	Submeter	Submeter			Road alignment	1 point/sec 3–5 Meters	Environmental features	52 feet
PA DOT								
SEMCOG								
St. Cloud Area Plan								
TN DOT	1:100000			± 40 feet	Road centerline	± 30 feet		
UT DOT			Submeter		Road centerline, rights-of-way	± 1 Meter ± 2 cm	Wetland banking	± 30 Meters
WA DOT 1		Submeter					Wetland delineation	Submeter
WA DOT 2					Riparian zone location	± 1 Meter	Water treatment facilities	

DATA COLLECTION—ACCURACY *(Continued)*

WA DOT 3				3 to 5 feet	Interchange and ramp location	3 to 5 feet		
WA DOT 4		Submeter			Airborne GPS	Submeter		
WA DOT 5							Wetland delineation	
Wasatch Fron Reg C					Traffic congestion mapping	Hundreds of feet		
WVA DOT								
WY DOT								

DATA COLLECTION—GPS GUIDES

Data Collection (Rules)

Agency	GPS Collection Rules 1	Rules 2	Rules 3	Accuracy Standards
AK DOT				NGS
AZ DOT				
CATS				
CT DOT 1				
CT DOT 2	Obstruction survey	Observation planning	Avoid redundancy in observation	
CT DOT 3				
CT DOT 4				
DE DOT				
FL DOT	Be consistent in the data collection process	Continually monitor the status of the satellites and the data collected	Closely examine the data for validity as it is being recorded	
GA DOT				
GA DOT IT Div	Must know application accuracy	Know the limitations of your GPS hardware and software	Always check your equipment and data for inaccuracies, human error, poor measurements	GA GE Data Clearing house
HI DOT				
KPMG	Do not view data collection screen while driving	Plug in correctly and achieve satellite lock	Operate vehicle normally	
KS DOT	Avoid large structures	Stay at least 2.5 miles from transmitter towers	Stay away from high voltage transmission lines	NGS
KY Trans				NSSDA
LA DOT				NSSDA
MD DOT 1	Use NAD83	Export GPS data to usable GIS format		
MD DOT 2	Tie to HARN network	Tie to vertical network	Use NAD83/91	NGS
ME DOT	Capture centerline position	Capture approach to new roads to portray angle of intersection	Record variations in driving	
Metro Wash COG				
MI DOT				
MS DOT				
MT DOT	Must obtain 4 satellites	PDOP < 4		
MTC	Utilize differential connection unit that was accurate to $\pm$ 10 M	Follow manufacturers guidelines		
ND DOT	Must collect in real-time	PDOP < 4		
NE Road Dept.				Navstar Mapping Corp.
NH DOT	Must differentially correct data	PDOP ≤ 6, Number of satellites = 4, Research optimum collection time	Collect line features at 1 point per second	NGS
NYS DOT	Must obtain 5 satellites	Research optimum collection time	Use elevation mask of 23 degrees and collect for two minutes	FGDC, NGS
OK DOT				
OR DOT	Create a recognizable data file for data collection	Collect line features at 1 point per second	The person that collects the data must edit the field data	

DATA COLLECTION—GPS GUIDES*(Continued)*
Data Collection (Rules)

PA DOT				
SEMCOG	No data collection during rain or snow	Use safety lights on vehicle	Use of daily log	
St. Cloud Area Plan				
TN DOT	Spend an adequate amount of time on line features	Create offset for height of instrument	Adjust data collection epoch rate depending on occupation time	
UT DOT	Record data of collection and unit used	Record methodology	Record projection and spheroid	USGS
WA DOT 1				
WA DOT 2	Avoid large structures	Charge unit before leaving and bring extra batteries	If not tracking enough satellites, raise antenna or move 1–2 feet in any direction	USGS
WA DOT 3	Drive in left lane	Static point for beginning and end of route		
WA DOT 4	Data collected according to NSDI standards	Use NGS height modernization program		State Statute and NSSDA
WA DOT 5	Research optimum collection time			Fed Geodetic Control Sub
Wasatch Fron Reg G	Drive the assigned route without detour	Operate vehicle as normal	Drive the route at peak congestion time	
WVA DOT				
WY DOT				

DATA PROCESSING—PROJECTION, DATUM, AND COORDINATE SYSTEM

Agency	Standard Projection	Standard Datum	Most Frequently Used System
AK DOT	UTM	NAVD88	State Plane
AZ DOT	Geographic	NAD 83, 86 adj	State Plane
CATS	Other	NAD 27	State Plane, Lat-Long
CT DOT 1			State Plane
CT DOT 2	Other	NAD 27	State Plane
CT DOT 3			
CT DOT 4		NAD 83, 86 adj	State Plane
DE DOT			
FL DOT	UTM, Albers	NAD 83, 86 adj	Albers
GA DOT		NAD 83, 86 adj	
GA DOT IT Div	UTM, Geographic	NAD 27	Lambert
HI DOT	Geographic	Hawaiian	State Plane, Local System
KPMG	Other	NAD 27	Directional Cosines
KS DOT	Geographic	NAD 83, 86 adj	Ground Coordinates
KY Trans	Other	NAD 83, 86 adj	State Plane
LA DOT	Geographic	NAD 83, 86 adj	State Plane, Polyconic
MD DOT 1	Geographic	NAVF 88, Ellipsoid Heights, Other	State Plane, NAD 83
MD DOT 2	UTM	NAD 27, NAD 83, 86 adj	State Plane, NAD 27 & 83
ME DOT	UTM	NAD 83, 86 adj	
Metro Wash COG		NAD 83, 86 adj	State Plane
MI DOT	UTM	NAD 83, 86 adj	State Plane, Local System
MS DOT	Other	NAD 83, 86 adj	Transverse Mercator, Lat-Long
MT DOT		NAD 83, 86 adj	State Plane
MTC	UTM	NAD 83, 86 adj	
ND DOT	UTM	NAD 83, 86 adj	
NE Road Dept.	Other	NAD 27	Lambert
NH DOT	Other	NAD 83, 86 adj, NGVD 29, Other	State Plane, NAD 83
NYS DOT	UTM	NAD 27, NAD 83, 86 adj, NAVD 88, Ellipsoid	State Plane
OK DOT		NAD 83, 86 adj	State Plane, UTM
OR DOT	Other	NAD 83, 86 adj	State Plane, Lambert
PA DOT	Other	NAD 83, 86 adj	State Plane, Polyconic
SEMCOG	Geographic		State Plane

DATA PROCESSING—PROJECTION, DATUM, AND COORDINATE SYSTEM *(Continued)*

St. Cloud Area Plan		NAD 83, 86 adj	
TN DOT	Other	NAD 27, NAD 83, 86 adj, NAVD 88, Other	State Plane, Lambert
UT DOT	UTM	NAD 27	State Plane
WA DOT 1	Other	NAVD 88, Other	WSDOT Project Datum, NAD 83
WA DOT 2	Geographic	NAD 83, 86 adj	State Plane, Local System
WA DOT 3	Geographic	NAD 83, 86 adj	State Plane
WA DOT 4	Geographic	NAD 83, 86 adj, NAVD 88, Other	State Plane, NAD 83 State Plane projected to a ground (proj) datum using scale and el factors
WA DOT 5		NAD 83, 86 adj	
Wasatch Fron Reg C	UTM	NAD 27	
WVA DOT			
WY DOT			

DATA PROCESSING—REVIEW, SMOOTHING, AND USE

Agency	Method of Cleanup	Uncorrected Data Use	Real-Time Data Use	Post-Processing Software
AK DOT		No	Horizontal and vertical control	Trimble software
AZ DOT			Road centerline, mile post location	In-house program and Arcview
CATS		No	No	
CT DOT 1	Uncorrected data are rotated			Yes
CT DOT 2		No		
CT DOT 3				
CT DOT 4				Trimble software
DE DOT				
FL DOT	Manually removed	No	Road inventory	No
GA DOT		Test GPS vs. DOQQ maps	Road centerline	
GA DOT IT Div		Low accuracy applications	Road centerline	Trimble, Magellan MSTAR
HI DOT				Trimble software, Starnet GPS
KPMG	Smoothing algorithms, logic checks, traffic rules	Raw GPS used for cost savings	Yes	Yes
KS DOT		No		
KY Trans		No		
LA DOT		No	Topographic surveys	Ashtech, GPPS, Omni
MD DOT 1		No	Photo control	Ashtech
MD DOT 2				Trimble software
ME DOT	Manually removed	No	Yes	Yes
Metro Wash COG	Manually removed	No		
MI DOT		No	No	Trimble software
MS DOT			Road alignment	Trimble software
MT DOT				Yes
MTC	Compared to base map, manually removed	Small scale mapping	Mapping	Creation of a geocode file
ND DOT		No	No	No
NE Road Dept.	Post-processing software, auxiliary sensors	No	Obtaining road track and feature points	Navstar Mapping Corp.
NH DOT	Manually removed	No	Rock cut, quarry bridge, test boring, and centerline locations	Trimble software
NYS DOT	Evaluate SD and RMS stats	No		
OK DOT	Algorithms	Collision locations	Skid resistance point locations	
OR DOT	Manually removed, manual smoothing	No	Field point collection	Trimble software

DATA PROCESSING—REVIEW, SMOOTHING, AND USE *(Continued)*

PA DOT				
SEMCOG		No		
St. Cloud Area Plan				
TN DOT		No	Road centerline	Yes
UT DOT		Wetland delineation	Road inventory	Yes
WA DOT 1	NGS Standards	No		
WA DOT 2	Re-collect data	No	Yes	Trimble software
WA DOT 3	Manually removed	Yes		
WA DOT 4		No	RTK local base station	Trimble software
WA DOT 5	Manually removed	No		Yes
Wasatch Fron Reg C	Data are removed	No		
WVA DOT				
WY DOT				

DATA PROCESSING—POST-PROCESSING, PROTOCOLS, AND RULES

Agency	Post-Processing Tasks	Internal Protocols	External Protocols	Unwritten Rules
AK DOT	Average location, identify bad data	No	NGS	
AZ DOT		Yes		
CATS		No		
CT DOT 1		No		
CT DOT 2		No		
CT DOT 3		No		
CT DOT 4	Average location, drop bad data, smooth data	No	No	Static data collection = 30 sec min
DE DOT		No		
FL DOT		No		Process data as little as possible
GA DOT		No		
GA DOT IT Div	Average location, drop bad data, identify bad data, smooth data	No		Use good control point, base station
HI DOT	Average location, drop bad data, identify bad data	No		
KPMG	Drop bad data, smooth data, other	Yes		Keep speed, bearing, time and lat/long data
KS DOT		No		
KY Trans	Average location, drop bad data, identify bad data, smooth data	Yes		
LA DOT	Average location, drop bad data, identify bad data, smooth data	No	NGS	
MD DOT 1	Other	No		Tie all GPS points to HARN
MD DOT 2	Average location, identify bad data, smooth data	No		
ME DOT	Average location	No		
Metro Wash COG	Average location, drop bad data, smooth data	Yes		
MI DOT	Average location, identify bad data	No		
MS DOT		No		
MT DOT	Average location, identify bad data, smooth data	No		
MTC	Other	No		
ND DOT		No		
NE Road Dept.	Average location, drop bad data, smooth data	Yes	Navstar Mapping Corp.	
NH DOT	Average location, identify bad data	No		Obtain lowest possible SD when averaging points preferably < 1 or 2
NYS DOT	Average location, identify bad data, smooth data	No		Use the closest GPS base station with 150 km of project
OK DOT		No		
PA DOT	Average location	No	No	

DATA PROCESSING—POST-PROCESSING, PROTOCOLS, AND RULES *(Continued)*

SEMCOG	Drop bad data	No	No	Clean data as soon as possible
St. Cloud Area Plan		No		
TN DOT	Average location, drop bad data, identify bad data	Yes	Leica Ski Training manuals	
UT DOT		No		
WA DOT 1		No		
WA DOT 2	Drop load data, identify bad data, smooth data	No		Use same base station for all files in a project
WA DOT 3		No		
WA DOT 4	Average location, identify bad data, smooth data	No	NGS	Follow NGS standards
WA DOT 5	Drop bad data, identify bad data	Yes	Navstar Mapping Corp.	
Wasatch Fron Reg C	Drop bad data, smooth data	No		
WVA DOT		No		
WY DOT		No		

GPS/GIS INTEGRATION

Agency	Digital Base Map	GIS/GPS Integration	Common Problems	Common Fixes
AK DOT	Yes	Kinematic		
AZ DOT	Yes	Static	Attributing arcs, intersecting arcs	Mend data to GPS
CATS	No			
CT DOT 1	Yes	Static		
CT DOT 2	No			
CT DOT 3	No			
CT DOT 4	Yes	Kinematic	Spatial mismatch	Manual adjustments
DE DOT	No			
FL DOT	Yes	Static		
GA DOT	Yes	Kinematic	Lack of training, different coordinate systems	
GA DOT IT Div	Yes	Kinematic	Inaccurate base map, intersecting arcs	
HI DOT	No			
KPMG	Yes		Inaccurate base map, simple network, missing streets	Rubbersheet GPS data to GIS
KS DOT	Yes	Static	Spatial mismatch	Reprojection of data Not resolved at present; looking at satellite imagery purchases
KY Trans	Yes	Kinematic		
LA DOT	Yes	Kinematic	Lack of training and experience	
MD DOT 1	No			
MD DOT 2	Yes	Kinematic	GPS data not smooth	Heads up digitizing
ME DOT	Yes	Kinematic	Inaccurate base map	Collection of more GPS points
Metro Wash COG	Yes	Kinematic	Spatial research	
MI DOT	Yes	Kinematic	Inaccurate data, missing roads	
MS DOT	Yes	Static		
MT DOT	Yes	Kinematic		
MTC	Yes	Static	Inaccurate GPS points	Re-collect data
ND DOT	Yes	Kinematic		
NE Road Dept.	Yes	Kinematic		
NH DOT	Yes	Static	Inaccurate base map, data conversion	Maintain GPS data locations
NYS DOT	Yes	Static	Spatial mismatch, data conversion	
OK DOT	Yes	Kinematic	Inaccurate base map, data conversion	Rubbersheet GIS to GPS
OR DOT	Yes	Kinematic		

GPS/GIS INTEGRATION *(Continued)*

PA DOT	Yes			
SEMCOG	Yes	Static		
St. Cloud Area Plan	Yes			
TN DOT	Yes	Kinematic		
UT DOT	Yes	Kinematic, Static	Location importance, large amounts of data	
WA DOT 1	No			
WA DOT 2	Yes		Inaccurate base map	Convert GPS to internal linear referencing system
WA DOT 3	Yes	Kinematic	Low resolution base map, topological errors	Manual adjustments
WA DOT 4	Yes	Kinematic	System works only in decimal degrees	Manual adjustments
WA DOT 5	No			
Wasatch Fron Reg C	Yes	Kinematic	Inaccurate base map, flawed network	Manual adjustments
WVA DOT	No			
WY DOT	No			

APPENDIX C

Oregon DOT Standards for GPS Data Collection

Global Positioning System (GPS) Inventory Standards

Author: Erick Cain, Darrell Haugeberg, and Dan Binder in cooperation with the Transportation Data Section Road Inventory and Classification Services Unit

Version Date: March 17, 2000

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APPENDIX D

State of Tennessee Department of Transportation Metadata Standards

Metadata
Tennessee Department of Transportation
Mapping Section

IDENTIFICATION_INFORMATION:
ORIGINATOR =
    Tennessee Department of Transportation, Planning Division, Mapping Section
    GEOSPATIAL_DATA_PRESENTATION_FORM = map
DESCRIPTION =
    The Digital Graphic is a vector line file for a county geographic unit georeferenced to the Tennessee State Plane Coordinate System, 1927 grid.
PURPOSE =
    For use as a source or background data in a GIS, as a means to perform quality assurance on other digital products, and as a source for the creation of special purpose maps. The data can also be merged with other digital data, e.g., DEM's, DOQ's, and DRG's to produce a hybrid digital file
SUPPLEMENTAL_INFORMATION =
    The State Plane Coordinate System 1927 feet
SPATIAL_DOMAIN = The data is collected digitally in county unit.
USE_CONSTRAINTS =
    Acknowledgement of the Tennessee Department of Transportation, Planning Division, Mapping Section would be appreciated in/on products derived from these data.
POINT_OF_CONTACT:
CONTACT_ORGANIZATION =
CONTACT_ADDRESS:
    ADDRESS_TYPE = mailing address
    ADDRESS = Suite 1000, James K. Polk Building
    CITY = Nashville
    STATE_OR_PROVINCE = TN
    POSTAL_CODE = 37243-0344
    CONTACT_VOICE_TELEPHONE = 1 615 741 3214
    CONTACT_FACSIMILE_TELEPHONE = 1 615 532 0353
    CONTACT_ELECTRONIC_MAIL_ADDRESS = shankins@mail.state.tn.us
    Copies of this metadata will be available through the TDOT Homepage at a future date.

DATA_QUALITY_INFORMATION = Tennessee Department of Transportation, Planning Division, Mapping Section
    The Digital Graphic is derived from 7.5 min. quadrangle maps, aerial photography, Global Positioning Satellite (GPS) system, roadway design plans, subdivision plats, boundary survey descriptions and field surveys. The Digital Graphic is created by table digitizing procedures using the above sources.
COMPLETENESS_REPORT =
    The Digital Graphic is a digital representation of the original source data. The intent is to create collected features as near as possible to their correct earthly location. The objective is to meet National Map accuracy standards. Data completeness for graphic files reflect content of the source data. Features may have been eliminated or generalized on the source graphic, due to scale and legibility constraints.
For information on National Map accuracy standards and data collection criteria, see:
U.S. Geological Survey, 1994, Standards for 1:24,000-Scale Digital Line Graphs and Quadrangle Maps: National Mapping Program Technical Instructions and U.S. Geological Survey, 1994, Standards for Digital Line Graphs: National Mapping Program Technical Instructions.

DIGITAL_FORM:
    DIGITAL_TRANSFER_INFORMATION:
    FORMAT_NAME = MICROSTATION 5.0 compatible
    FORMAT_FILE_EXTENTION = .dgn or .bas

POSITIONAL_ ACCURACY:
    HORIZONTAL_POSITIONAL_ACCURACY_REPORT =
        The horizontal positional accuracy is that of the original source maps or data. The coordinate system of the Digital Graphic is State Plane Coordinate System, NAD 1927
    VERTICAL_POSITIONAL_ACCURACY_REPORT = not applicable.

Metadata
Tennessee Department of Transportation
Mapping Section

PROCESS_STEP = The process steps used in the production of the standard datasets.

1. Production of a Digital Graphic begins with the assembly of all the paper source data and any computer based data available for the coverage unit.

2. All features are digitally computed in their respective geographic location and assigned the appropriate attribution based on the TDOT standard.

3. The TDOT standard attribution consists of feature separation by level, color, line weight, line style. Data sets can also be separated by design file/reference file.

Level	Color	Line Weight	Line Style	Font	Text Height-ft	Feature Description
1	7	15	5			Interstate Highways-centerline of divided hwy
1	7	6	0			Interstate Highways-separate lanes
2	3	15	5			State Primary Highways-centerline of div. hwy
2	3	6	0			State Primary Highways-separate lanes
2	3	6	0			State Primary Highways-centerline-nondivided
3	2	15	5			State Secondary Highways-centerline of div. hwy
3	2	6	0			State Secondary Highways-separate lanes
3	2	6	0			State Secondary Highways-centerline-nondivided
4	4	8	5			Collector Routes; paved, divided hwy
4	4	8	0			Collector Routes; paved, nondivided hwy
8	19	5	5			Collector Routes; divided hwy. not paved
8	19	5	0			Collector Routes; not paved
5	15	8	0			FA Routes, Urban Classified; divided hwy
5	15	8	5			FA Routes, Urban Classified; paved
9	20	5	0			FA Routes, Urban Classified; not paved
6	8	8	5			Local City Streets; divided hwy
6	8	8	0			Local City Streets; paved
25	21	5	0			Local City Streets; not paved
7	23	8	5			Local County Roads; divided hwy
7	23	8	0			Local County Roads; paved
10	22	5	0			Local County Roads; not paved
26	24	8	5			State Park and Reservation Roads; divided
26	24	8	0			State Park and Reservation Roads; paved
26	28	5	0			State Park and Reservation Roads; not paved
11	6	6	0			Ramps; Interstate Highways
12	6	6	0			Ramps; State Primary Highways
13	6	6	0			Ramps; State Secondary Highways
14	6	6	0			Ramps; Collector Routes & FA Routes
		Line	Line		Text	

Metadata
Tennessee Department of Transportation
Mapping Section

Level	Color	Line Weight	Line Style	Font	Text Height-ft	Feature Description
45						Not Used in this dataset
46	0			1	75	Road Name Text
47	2					State Secondary Highway Markers
48	11			23	90	Railroad Name Text
49	1			23	90	Major Water Name Text
50	14			23	90	Minor Water Name Text
51	15	1	5			Urban Street-Multilane undivided
52	20			1	75	River Bend And Island Name Text
53	0					County Seat Symbol
54	7					Various Roadside Feature Symbols
55						Not Used in this dataset
56	12					Control Point Monuments (7.5 min. Quad. Corners)
57						Not Used in this dataset
58						Not Used in this dataset
59						Not Used in this dataset
60						Not Used in this dataset
61						Not Used in this dataset
62	0	8	2			Public Roads–NOT City or County Maintained
63						Not Used in this dataset

4. The TDOT reviews all datasets before maps are made and published. Every possible check is made to ensure the correctness and completeness of each dataset.

HORIZONTAL_COORDINATE_SYSTEM_DEFINITION:
  PLANAR:
    GRID_COORDINATE_SYSTEM:
    GRID_COORDINATE_SYSTEM_NAME = State Plane Coordinate System 1927
    STATE_PLANE_COORDINATE_SYSTEM
    SPCS_ZONE_IDENTIFIER = 4100
    Lambert_Conformal_Conic
  PLANAR_DISTANCE_UNITS = feet

TDOT'S DATA EXCHANGE AND OR SWAPPING POLICY

Over the years we have received numerous requests from the public to use our maps or resell our maps. A policy (written) has never been developed. Please be advised that the map is not copyrighted, but we would request acknowledgment, from you that our map is being used and a disclaimer stating that TDOT has no affiliation with the business. We would also request a notice that the official map is available to the public free of charge. We also ask the requestor to make a note identifying any data added to the map or changed from the original we submitted for use. The user will be responsible for any conversion required for their use. We reserve the right to disapprove any use deemed as not in the best interest of the TDOT.

Metadata
Tennessee Department of Transportation
Mapping Section

DISTRIBUTION LIABILITY =

Although these data have been processed successfully on a computer system at the Tennessee Department of Transportation (TDOT), no warranty, expressed or implied, is made by the TDOT regarding the utility of the data on any other system, nor shall the act of distribution constitute any such warranty. The TDOT will provide delivery of this product in computer-readable format, and will offer appropriate suggestions on use constraints. However, if the product is determined unreadable by correctly adjusted computer input peripherals, the TDOT will not be responsible nor will TDOT furnish the dataset in any other format as a convenience to the requestor.

APPENDIX E

Summary of GPS–GIS Guidelines

Step	Travel Surveys	Speed Studies
1. Project Purpose and GIS Base Map Selection	• Predetermine spatial attribute characteristics • Select appropriate projection, scale, and datum • Check metadata for accuracy specifications	• Predetermine spatial attribute characteristics • Select appropriate projection, scale, and datum • Check metadata for accuracy specifications
2. GPS Data Collection	• Data collection driven by project purpose • Predetermine accuracy of GPS points and frequency of data collection • Train field personnel including knowledge of project purpose • PDOP < 4.0 and a minimum of four satellites • Collect data as frequently as possible (1-second intervals • Maintain constant lock on satellites; if satellite lock is a problem consider A-GPS • Collect data during leaf off season if possible • Place GPS in same position on all vehicles • Need to ensure each time trip begins that adequate time is allowed for time to first fix. • With SA turned off, differential correction may not be necessary. • Adequate time must be allowed for TTFF • All links of 3 m or wider should be included for travel survey • Intersection locations most important part of base map	• Data collection driven by project purpose • Drive routes prior to data collection to determine potential obstructions • Differential correction may not be necessary, especially with SA turned off • PDOP < 4.0 and a minimum of four satellites • Travel time runs on non-holiday weekdays (Tuesday–Thursday) • In general conduct runs during off-peak times • Field check corridors for obstructions and • Collect data during leaf off season if possible • Intersection locations most important part of base map • Use floating car technique • Base and rover GPS units should track identical satellites (DGPS only) • Conduct runs during good weather • Adequate time must be allowed for TTFF
3. Data Review and Smoothing	• Identify relationship between data collected and mapped data • Elimate bad, duplicate, and extraneous data points beyond a given threshold	• Use GPS provided speed instead of calculating it from Doppler algorithm. • Eliminate bad, duplicate, and extraneous data points beyond a given threshold
4. Map Matching	• If there are <15 valid GPS points for a given trip route may not be valid for map matching • One way to reduce overestimated travel distance is to collect data at 1-second intervals, then use less frequent rate (5,10 sec) to calculate travel distance • Define error threshold for map matching • Most common method to map match is manual adjustment of GPS points • If GPS points are consistently incorrect map may be moved to correct alignment	• Define error threshold for map matching • Most common method to map match is manual adjustment of GPS points • If GPS points are consistently incorrect map may be moved to correct alignment
5. Application and Output	• Need to enter some data, for example, number of passengers or driver identification, manually	
6. Data Maintenance and Improved GIS Base Map	• Retain original data from GPS for later use • If GPS data are known to be more accurate than base map, use GPS points to improve accuracy of base map • Keep base map current • Maintain current and accurate metadata	• Keep all original data from GPS for later use • If GPS data are known to be more accurate than base map, use GPS points to improve accuracy of base map • Keep base map current • Maintain current and accurate metadata

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APPENDIX F

Internet Sites

GPS

1. U.S. Coast Guard Navigation Center
   http://www.navcen.uscg.gov/

This website covers a broad spectrum of topics related to GPS including update information on satellites.

2. United States Naval Observatory
   http://tycho.usno.navy.mil/gps_datafiles.html

A site that provides timing data for individual GPS satellites and the satellite constellation. Also provides links to other GPS websites.

3. National Geodetic Survey
   http://www.ngs.noaa.gov/CORS/cors-data.html

The National Geodetic Survey (NGS), an office of NOAA's National Ocean Service, coordinates a network of continuously operating reference stations (CORS) that provide Global Positioning System (GPS) carrier phase and code range measurements in support of 3-dimensional positioning activities throughout the United States and its territories. Surveyors, GIS/LIS professionals, engineers, scientists, and others can apply CORS data to position points at which GPS data have been collected. The CORS system enables positioning accuracies that approach a few centimeters relative to the National Spatial Reference System, both horizontally and vertically.

4. Global Positioning System Overview–Peter H. Dana
   http://www.colorado.Edu/geography/gcraft/notes/gps/gps_f.html

This is an effective introduction to GPS and its applications.

5. GLONASS–Russian Federation GPS system
   http://www.rssi.ru/SFCSIC/

Background information and satellite status data of the Russian Federation GPS system. If used in conjunction with the U.S. system, it can provide better accuracy because more satellites are available to the user.

6. Texas Department of Transportation GPS Information
   http://www.dot.state.tx.us/insdtdot/orgchart/isd/gps/gps.htm

Data used by Texas DOT to post-process differential corrected GPS data.

GIS

1. Federal Geographic Data Committee
   http://www.fgdc.gov/

The website for standards related to mapping. There is a section on spatial data infrastructure implementation, as well as application standards. In addition there is a section on metadata.

2. University Consortium for Geographic Information Science
   http://www.ucgis.org/

An organization that links universities together to advance the development of GIS. A good resource group for advanced topics.

3. Positional Accuracy Handbook
   http://www.mnplan.state.mn.us/press/accurate.html

An excellent presentation on methods that can be used to maintain and improve accuracy in digital mapping. Sponsored by Minnesota Planning.

4. New York State Department of Transportation
   http://www.dot.state.ny.us/magis/magis.html

Site contains information on digital and paper maps prepared by NYDOT

5. TIGER Line files
   http://www.census.gov

Although TIGER files are not known for their accuracy, their price (free) and their ubiquitous coverage of the United States, including streets and highways, census geography, and political boundaries are an excellent beginning point for community mapping. This is especially true if there is a need to map socioeconomic data for environmental justice issues.

6. United States Geological Survey
   http://mapping.usgs.gov/

Listing of map products, resources, and services of the nation's largest mapping agency.

7. Arizona Department of Transportation
   http://map.azfms.com/atismain.html

Information about GIS activities that are prepared with the Arizona Transportation Information System (ATIS).

THE TRANSPORTATION RESEARCH BOARD is a unit of the National Research Council, a private, nonprofit institution that provides independent advice on scientific and technical issues under a congressional charter. The Research Council is the principal operating arm of the National Academy of Sciences and the National Academy of Engineering.

The mission of the Transportation Research Board is to promote innovation and progress in transportation by stimulating and conducting research, facilitating the dissemination of information, and encouraging the implementation of research findings. The Board's varied activities annually draw on approximately 4,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

The National Academy of Sciences is a nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encouraging education and research, and recognizes the superior achievements of engineers. Dr. William A.Wulf is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences, by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce Alberts and Dr. William A. Wulf are chairman and vice chairman, respectively, of the National Research Council.