Integration of GPS with Remote Sensing and GIS: Reality and Prospect

Jay Gao

Abstract

The advent of the Global Positioning System (GPS) technology has not only enhanced the ease and versatility of spatial data acquisition, but has also diversified the approaches by which it is integrated with remote sensing and geographic information systems (GISs). In this paper the necessity of integrating GPS, remote sensing, and GIS is discussed following their definition. The current status of integration is reviewed under four proposed models: linear, interactive, hierarchical, and complex. Applications of integration are reviewed under three categories: resources management and environmental monitoring, emergency response, and mobile mapping. This paper reveals that linear integration is the most common. Hierarchical integration has found applications in precision farming and environmental modeling. The complex mode of integration is most valuable in diaster mitigation, emergency response, and mobile mapping. With limited cases in hierarchical and complex models, the full potential of integration has not been achieved. The prospects of integration are distributed mobile GISs and location-aware multi-media digital personal assistants. As mobile communications technologies improve, full integration will find more applications in many new fields after removal of the obstacles in integration.

Introduction

The integration of remote sensing and Geographic Information Systems (GISs) has received considerable attention in the literature. Ehlers *et al.* (1989) first reviewed the necessity of integrating remote sensing with GIS, and discussed the potential of integration in resource management and environmental monitoring. Two years later Ehlers *et al.* (1991) further elaborated on how to make remote sensing data available and useful to GIS users. Lunetta *et al.* (1991) addressed the issue of errors stemming from data processing, analysis, conversion, and presentation in integration. They also identified research issues arising from integration. Recently, Hinto (1996) reviewed the historical evolution toward a closer integration of GIS with remote sensing for environmental applications, and software requirements in combining raster remote sensing and vector GIS data. Wilkinson (1996) comprehensively reviewed current issues in the integration of remote sensing and GIS with an emphasis on how GIS technology should cope with increased capability in remote sensing data acquisition.

In the late 1980s a new technology, the Global Positioning System (GPS), became a valuable tool in spatial data acquisition. This emergence has not only confounded the approaches by which it is integrated with remote sensing and GIS but also diversified the fields to which its integration with them has been applied. Thanks to the integrated use of GPS, remote sensing, and GIS, more and more research problems in resource management and environmental modeling can be tackled with increasing ease. In addition, the approaches by which these three techniques are integrated have become more complicated.

The objective of this paper is twofold:

- To conceptualize the diversity in integrating the three technologies through a review of the existing literature. This conceptualization will help to identify the areas in which their integration has proved the most valuable, and reveal the extent to which their potential has been realized. The conceptualization will also enhance our understanding of how they can be further integrated to fulfil new applications; and
- To identify the prospect of the integration, including the obstacles to be overcome to achieve total integration and to determine the areas that will benefit from the total integration.

In this paper remote sensing, GIS, and GPS are first defined. Through these definitions, the necessity of their integration is justified. Next, all possible methods by which the three disciplines have been integrated are summarized and presented graphically. Four models of integration (linear, interactive, hierarchical, and complex) are proposed and evaluated. The applications involving different integrations are systematically and comprehensively reviewed. Next, the prospect of full integration is discussed, together with the obstacles to overcome. Finally, the paper ends with the summary and discussion section.

Definition

Before any discussion on the integration of GPS, remote sensing, and GIS can begin, they must be defined precisely first. With the longest history among the three disciplines, remote sensing has been defined in a variety of ways in the literature. Colwell (1983) regarded it as "the gathering and processing of information about the Earth's environment, particularly its natural and cultural resources, through the use of photographic and related data acquired from an aircraft or satellite." Lillesand and Kiefer (1994) defined it as "the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in direct contact with the object, area, or phenomenon under investigation."

Department of Geography, University of Auckland, Private Bag 92019, Auckland, New Zealand (jg.gao@auckland.ac.nz)

Photogrammetric Engineering & Remote Sensing
Vol. 68, No. 5, May 2002, pp. 447–453.

0099-1112/02/6805–447$3.00/0

Campbell (1987) defined it as "the science of deriving information about the Earth's land and water areas from images acquired at a distance. It usually relies upon measurement of electromagnetic energy reflected or emitted from the features of interest." In this paper the definition of remote sensing is broadened to include image processing systems designed specifically for the analysis of remotely sensed data.

Just as with remote sensing, GIS does not have a universally accepted definition either. Goodchild (1985) thought GIS was "a system that uses a spatial database to provide answers to queries of a geographical nature." Cowen (1988) defined it as "a decision support system involving the integration of spatially referenced data in a problem solving environment." Stephens (1991) regarded it as "a digital system for the analysis and manipulation of a wide range of geographic data with associated subsystems for other forms of input and display, used in the context of decision making." Burrough and McDonnell (1998) referred it as "a powerful set of tools for collecting, storing, retrieving at will, transforming, and displaying spatial data from the real world for a particular set of purposes."

Due to its short history of existence, GPS does not have as many diverse definitions as do remote sensing and GIS. Wooden (1985) defined it as "an all-weather, space-based navigation system under development by the Department of Defence to satisfy the requirements for the military forces to accurately determine their position, velocity, and time in a common reference system, anywhere on or near the Earth on a continuous basis." Bock (1996) described the purpose of GPS as "to provide a global absolute positioning capability with respect to a consistent terrestrial reference frame." The precise determination of location relies on satellites and ground stations. With the proper use of equipment, GPS positioning accuracy can be better than a meter.

Necessity of Integration

Despite its various definitions, GIS distinguishes itself from the other two technologies in that it enables data from diverse sources to be integrated, analyzed, and even modeled owing to its powerful analytical functionality. These functions, however, cannot be fully realized if the GIS database is incomplete, inaccurate, or obsolete. By their nature, the data contained in a GIS database are either spatial (e.g., administrative boundaries and boundaries of land-cover parcels) or thematic (e.g., types of land cover). Traditionally, spatial data and some thematic data associated with them are digitized from existing topographic or land-use maps. Nevertheless, these maps are secondary in nature. They may not show all desired features because of map generalization. Second, topographic or land-use maps may be obsolete due to rapid changes on the ground. These limitations can be overcome with the use of remote sensing and/or GPS. Aerial photographs and satellite images are original and are able to offer more current areal-based data than do topographic and thematic maps, while GPS is an efficient method of collecting data in a timely fashion.

One element common to all definitions of remote sensing presented in the preceding section is its data acquisition functionality. Original aerial photographs and satellite images, digital or analog, are geographically referenced to their own coordinate systems. They must be geo-referenced to a common coordinate system or to a universal system if a phenomenon or area is to be studied from multiple frames of images, or if these data are to be spatially overlaid with data from other sources. Georeferencing requires some kind of geometric control on the ground. Traditionally, geometric control for remote sensing imagery has been derived from topographic maps because they are readily available and geometrically reliable. Nevertheless, topographic maps are completely ineffective in areas where no distinct landmarks are present or where the scene has undergone drastic changes since the publication of the maps. In this case, GPS can be used as an efficient alternative for obtaining spatial data that are automatically referenced to a universal coordinate system. Point, linear, or even areal data may be obtainable in a real-time or near-real-time fashion. Point-based data at selected landmarks, commonly known as ground control points (GCPs), may be used to geo-reference remotely sensed images. GPS data, even if areal in nature, can by no means replace aerial photographs or satellite images because of their inability in obtaining truly 2D areal data.

The above discussion illustrates that remote sensing, GIS, and GPS are intrinsically complementary to one another in their primary functions. Each of the technologies has its limitations. If applied individually, it may be troublesome or impossible for each technology to function properly in certain applications. Only through integration can their strengths be fully utilized. Integration will not only ease their applications in resource management and environmental monitoring (e.g., wild fire fighting), but also broaden the scope to which they are applicable (e.g., real-time emergency response). As a matter of fact, the integration of GPS, remote sensing, and GIS in combination with ground monitoring systems has proved to be an efficient method of managing, analyzing, and outputting spatial data for regional water resources management (Chen *et al.*, 1997). Such an integration is indispensable in devising an effective approach for selectively applying pesticides and fertilizers to improve farming efficiency and reduce environmental hazards (Runyon, 1994).

Models of Integration

The diverse methods for the integration of remote sensing, GPS, and GIS, as has been described in the literature, can be conceptulized and summarized by four models: linear, interactive, hierarchical, and complex. They are elaborated on below.

Linear Model

Data flow linearly from GPS to remote sensing and ultimately to a GIS in the linear model (Figure 1). In this model the unique strength of each component is utilized to the maximum. That is, GPS is used to obtain geometric control for aerial photographs and satellite imagery. Rectified photographs and images are then integrated into a GIS database. The linear structure of the model implies that the three components are not equally important. A GIS, being the final destination of the integration, plays a dominant role. Rectified images form part of the GIS database. All of the spatial analyses and modeling are carried out in the GIS. By comparison, the role of GPS is subordinate in that it supplies point-based data to remote sensing. In the final GIS database, GPS-derived data are not visible due to the absence of a direct connection between GPS and GIS. In this sense, GPS data serve to bridge the gap between remote sensing data and other data in the GIS database. They are used to standardize satellite images and aerial photographs to a geo-referencing system used by other GIS data.

In this model, the integration of GPS data with remote sensing occurs in three temporal modes—simultaneous, independent, and post-processing—all of which take place prior to integration with a GIS. Simultaneous integration is commonly utilized in recording remotely sensed data in which a GPS unit is mounted on an aircraft to navigate to the study area and to obtain the position and orientation parameters of the sensor (Monday *et al.*, 1994). For instance, the GPS unit is able to direct the pilot along flight lines, fire cameras at a fixed distance interval, and record the coordinates of every photograph (Biggs *et al.*, 1989). These parameters are used to rectify the acquired remote sensing data or to triangulate the aerial photographs. The use of GPS avoids costly operations in building ground control for aerial triangulation (Ackermann and Schade, 1993; Colomina, 1993). In addition to aiding in the acquisition of stereoscopic aerial photographs, simultaneous integration has

Figure 1. The linear model of integration.

also found applications in video remote sensing (Thomas, 1997). The integration of a GPS receiver into remote sensing data acquisition offers flexibility, allowing more information to be acquired with less time and effort, and thus achieving a high productivity.

The independent mode of integration applies to remotely sensed images that have already been acquired. They are geo-referenced using GPS-acquired coordinates that are logged independently from the remote sensing data recording. The accuracy of integration is affected by the number of GCPs logged, whether GPS coordinates are differentially corrected (Welch *et al.*, 1992; Welch *et al.*, 1995), and the performance of the GPS receiver used (Clavet *et al.*, 1993). Errors inherent in raw GPS readings may be suppressed through averaging repeatedly logged coordinates, either differentially corrected or raw, of the same location (August *et al.*, 1994; Sigrist *et al.*, 1999). GCP coordinates averaged from as few as 30 loggings are able to achieve a higher integration accuracy than those obtained from a 1:20,000-scale topographic map (Gao, 2000).

Post-processing integration of remote sensing and GPS data occurs after remote sensing images have been analyzed. In the integration the remotely sensed land-cover maps or changes in land covers detected from multi-temporal remote sensing data are verified in the field with a GPS unit. Assessment of the accuracy of the land-cover maps requires ground-cover information at selected sites, which is obtained through field visits (Fallas and Savitsky, 1996). A portable GPS receiver can guide and locate sites of change identified from the overlay analysis of multi-temporal remote sensing images (Haack *et al.*, 1998).

Interactive Model

The interactive model bears a striking resemblance to the linear one in structure (Figure 2). Upon closer scrutiny, data flow mutually between GPS and remote sensing, and between remote sensing and GIS. The mutuality implies that the ultimate task of integration may be carried out in a raster GIS or in a digital image analysis system such as ERDAS Imagine®. Thus, remote sensing can no longer be perceived as a mere feeder of data to a GIS. Although it is possible for data to flow from a GIS to remote sensing in this model, left-to-right integration is much more common than is data flow in the opposite direction, as the arrow width in Figure 2 implies. The interactive nature among GISs and remote sensing makes it difficult to judge their relative significance, even though GPS as a data collection method is considered less important. Contrary to the linear model, GPS data may be overlaid with remote-sensing-derived results to map features such as roads that are invisible on satellite imagery due to their coarse spatial resolution (Treitz *et al.* 1992). In this case, GPS data are directly visible in the GIS database after integration.

The integration of remote sensing with GIS is exemplified by detection of land-cover change through the overlay of historic and current land-cover maps in a GIS (Welch *et al.*, 1992; Haack *et al.*, 1998). The integration of GIS with remote sensing has been applied to facilitate image segmentation and classification using the information (knowledge) stored in a GIS database. Incorporation of ancillary data in the classification either overcomes limitations underpinning conventional parametric classifiers and those associated with the heterogeneity of the scene under study, or compensates for topographic effect. In either case, a higher accuracy is expected. The final mapping product may be integrated into a GIS for other applications, such as derivation of the percentage of impervious and pervious surfaces through overlay analysis (Monday *et al.*, 1994).

Hierarchical Model

There are two tiers of integration in the hierarchical model (Figure 3). The first tier of integration (overlay) occurs between GPS data and remote sensing imagery. In addition to the aforementioned rectification of remotely sensed images using GPS-derived coordinates, the rectified images are also used to characterize *in situ* samples according to their locations determined with a GPS receiver. Overlay of *in situ* samples with a digital photograph or satellite imagery helps to establish the association between the variable under study and its image properties (Usery *et al.*, 1995; Gao and O'Leary, 1997). Statistical relationship between the two variables may be established using a spatial analysis package such as S-Plus. The second tier of integration (modeling) involves remotely sensed data, other GIS data, and/or mathematical models. The task of spatial modeling can be implemented in remote sensing or a GIS, depending on the data format. A digital image analysis system allows modelings in the raster format to be carried out as readily as in a GIS. In this model of integration there is no direct link between a GIS and remote sensing. The role of remote sensing has become more dominant than GISs in raster-based applications. Remote sensing supplies the primary data needed for monitoring and modeling while the GIS supplements more data, and may also provide the environment in which the modeling is undertaken. GPS still plays a subordinate albeit expanded role because GPS data are not directly involved at the second tier of integration.

Complex Model

Containing all possible associations between any two components, the complex model represents the ultimate or total integration of GPS, remote sensing, and GIS (Figure 4). In addition to all links contained in the previous three models, there is an extra interaction between GPS and GIS. In this case, GPS data may

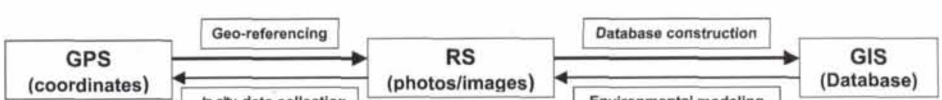

Figure 2. The interactive model of integration.

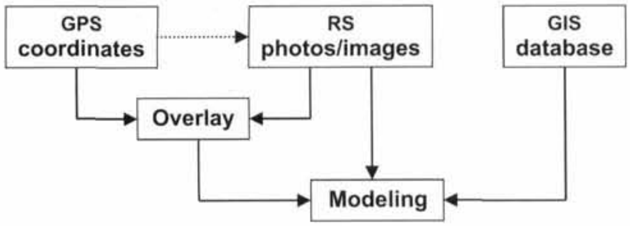

Figure 3. The hierarchical model of integration.

be directly exported to a GIS database to update it or to construct new databases (Bor, 1994). These data can be point, linear, or even areal. Their geometric properties must be transformed to those of the data already stored in the GIS database before the integration. This integration has found applications in precision farming in which a GPS receiver is used to measure coordinates associated with precision-farming variables while a GIS is used for data integration, storage, and analysis (Swindell, 1995; Lachapelle *et al.*, 1996). The integration of a GIS with GPS is similar to that between remote sensing and GPS. This association is initiated when the results from GIS modeling are substantiated in the field, or when more ground information at positions determined from the modeled results is collected in the field. The circular nature of integration makes it very difficult to judge the relative importance of each component. Each of the components can be of foremost importance, dependent upon the specific nature of an application.

Existing Applications of Integration

The value of integrating GIS, GPS, and remote sensing lies in those applications that require comprehensive and geo-referenced data current up to seconds or instantly. These applications include resources management and environmental monitoring, emergency response, and mobile mapping.

Resources Management and Environmental Monitoring

The integration of remote sensing, GPS, and GIS coupled with powerful computer modeling tools enables resources managers to better adapt to the dynamic, multi-use management complexities of natural resources. Integration empowers them to quantitatively model the resources and objectively analyze their multiple demands in nearly real time. Remote sensing is critical to acquiring data for the efficient management of natural resources such as forests. A digital database of native and exotic vegetation can be created from aerial photographs integrated with a GIS and GPS data (McCormick, 1999). GPS data

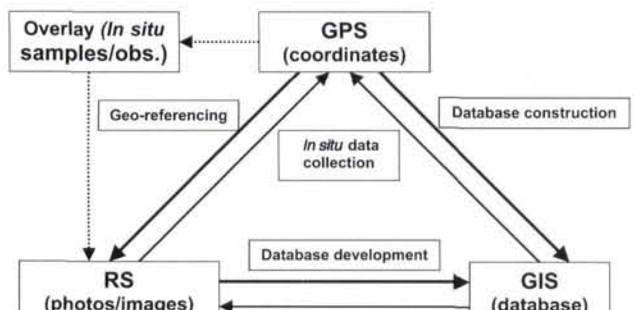

Figure 4. The complex model of integration.

supplement the rectification and interpretation of satellite and aerial images to be included in a forestry information system. Additionally, a comprehensive database incorporating all anticipated data requirements may be constructed from remote sensing and GPS data for the assessment of ground-water resources (Hardisty *et al.*, 1996). In such applications satellite imagery is used to generate base maps and initial surface hydrogeological interpretations, whereas ground truthing and point sampling data are obtainable using hand-held GPS units. The parameters in water resource models may also be estimated from remote sensing images in order to implement the modeling in a GIS (Chen *et al.*, 1997).

Precision farming is one application that can benefit from the integration of a GIS, satellite images, and GPS technologies, resulting in the reduction in the loss of nutrients from agricultural fields (Ifft *et al.*, 1995). The location of planned cropland areas and the associated database can be created from satellite imagery. Remote sensing images rectified using differentially corrected GPS coordinates have been integrated into a GIS to determine the property of *in-situ* biophysical samples from which suitability models of conifer habitat are created (McGregor, 1998).

One environmental application of integrating ground photographs with GPS data and a GIS is visualization of scenic resources (Clay and Marsh, 1997). This integration is achieved through locating with a GPS unit the ground positions from which photographs are taken. A series of three-dimensional surfaces can be produced from the scanned images in conjunction with site data. Monitoring of beach morphodynamics is another environmental application area that benefits tremendously from the integrated use of GPS and remotely sensed data in a GIS. The lack of distinct and stable landmarks in the coastal environment necessitates the use of GPS in building geometric control for remote sensing images. The development of an integrated resource database, in turn, enables coastal managers to evaluate proposed coastal management scenarios and make ecologically sound decisions (Welch *et al.*, 1991). Radiologically contaminated sites can be identified using portable gamma radiation survey instruments integrated with GPS equipment and GIS technology (Runyon *et al.*, 1994). Maps depicting these sites are produced in a GIS from coordinate data along with surface gamma radiation data. The proficient collection, integration, and predictive modeling of spatial data are vital to describing and monitoring environmental cleanup problems. Airborne remote sensors appear to have the greatest potential for meeting these environmental needs (Albers and Purdy, 1994).

Emergency Response

Emergency situations such as fires, accidents, and crime scenes require automatic vehicle navigation to the concerned spot. Profound breakthroughs in GPS and mobile communications combined with revolutionary developments in computer technology have led to the development of land navigation systems (Adams *et al.*, 1990). One of the most noteworthy applications of GPS and GIS in public safety is the Mayday system in which motorists can call for assistance without knowing their location in case of emergency (Carstensen, 1998).

In disaster mitigation, such as fire fighting and emergency evacuation, it is essential to have real-time geo-referenced information. In wildfire fighting, GPS and radio communications are used to track fire equipment and field personnel in real time, whereas integration of GPS and GIS with communications technology provides firefighters with operational resources (Ambrosia *et al.*, 1998). Real-time remote sensing data and near-real-time map integration and development can be relayed to a disaster control center. Surfaces affected by forest fires may be mapped from satellite imagery (Fernandez *et al.*, 1997). A GIS can be used to assess fire damage to soil and the environment and plan remedy measures after the fire. Imagery-derived results can be validated by GPS-logged perimeters of large fires. Ground and aerial observations can be integrated with digital images to produce maps of burn intensity in order to devise an appropriate rehabilitation program. Information on fire-induced watershed conditions may be gathered and mapped using GPS data, videography, aerial photographs, and satellite imagery (Lachowski *et al.*, 1997). GPS and satellite imagery produced data may be overlaid on GIS data layers to reveal details of burned property parcels (Difani and Dolton, 1992).

Effective hazard warning and disaster evacuation cannot function properly without the integration of the three technologies. Remote sensing and communications satellites are useful in disaster prevention, preparedness, and relief (Walter, 1990), and already provide operational capability for storm warnings and search-and-rescue efforts. Other capabilities, such as improved flood prediction and global mobile communications during relief, are almost within reach. Decisions related to floodplain management require a high-resolution digital elevation model (DEM) and floodplain-related GIS data layers. A high-resolution DEM may be generated using digitally scanned photos in conjunction with highly accurate ground control from a GPS survey (Sugumaran *et al.*, 2000).

Mapping and Mobile Mapping

Mapping of linear features (e.g., roads, pipelines, power lines, river networks, coastlines, etc) (Cooper *et al.*, 1995) and, to some extent, areal features, is achievable with GPS alone by logging data along the features or their perimeters. Special point features such as black mangrove populations can be mapped from geo-referenced video imagery in a GIS in terms of the latitude/longitude coordinates of mangroves (Everitt *et al.*, 1996). Furthermore, GPS and GIS in combination with aerial photographs can be used to accurately locate trees and to create appropriate maps that highlight individual trees and other landmarks (Kane and Ryan, 1998).

Road network plays an essential role in certain GIS applications (e.g., vehicle tracking) that require road or road related information. Road maps may be produced using innovative methods of combining GPS with digital orthophotography (Joffe, 1994). Mobile mapping systems have proven to be by far, the most accurate and efficient in automatically collecting road data and relating them to other information. Through a combination of GPS with digital cameras, a mobile mapping system is able to acquire geo-referenced images in a real-time fashion (Tao, 2000). This system consists mainly of a moving platform, navigation sensors, and mapping sensors (Li, 1997). The mobile platform can be a vehicle, a vessel, or an aircraft. A successful extension of this technology to helicopter-borne and airborne systems provides a powerful tool for large- and medium-scale spatial data acquisition and database updating. Navigation sensors (i.e., GPS receivers) track the vehicle and provide positional and orientational parameters of the mapping sensors. Spatial objects and their attributes are extracted from the geo-referenced mapping sensor data in the form of digital and video images either automatically on the mobile platform or during post-processing (Novak, 1995). The comprehensive set of multi-media information captured by mobile mapping systems can be used for highway and railway maintenance, softcopy photogrammetry, and utility mapping (Novak, 1993). Mobile mapping technology has evolved to such a stage that it is able to capture more information with less time and effort while still offering high flexibility in data acquisition (Li, 1997).

Prospects for Integration

One of the exciting prospects for the integration of GPS with remote sensing and GIS is the development of the location-aware personal digital assistant (PDA). This system consists of a hand-held computer that is equipped with a GPS receiver. Such classic information as roads and their geometry and attributes is stored in the GIS database (Van Essen and De Taeye, 1993). More innovative data include popular tourist attractions, with their ground and aerial photographs, as well as satellite imagery. Common applications of PDA are vehicle navigation, route planning, and tourism. Drivers can also rely on the system to find their way around. Another example of a PDA application is computer-assisted self-interview in which a PDA is used to capture vehicle-based daily travel information for the purposes of studying transportation (Murakami and Wagner, 1999). Data such as date, start time, journey duration, and vehicle position (latitude and longitude) are collected automatically at frequent intervals.

The location-aware PDA differs from automatic vehicle tracking and navigation in that the navigation is guided by voice. Furthermore, scenic views along the route of travel together with the current location of the vehicle and the road map of the immediate vicinity are displayed on the computer screen. The display may be periodically refreshed and automatically updated as the vehicle roams a route. The view outside the vehicle is able to reassure the driver that he or she is on the right track. Although such a multi-media location-aware PDA is not available at present, it could become a reality in the not too distant future. With the developments in mobile multi-media communications technologies, it is anticipated that the hand-held computer will some day be replaced with a cellular phone. In this case, the road map and scenic views will have to be extracted from a remote server rather than being stored locally.

Another prospect in integration is the distributed mobile GIS (DM-GIS) which is very similar to a PDA in principle (Karimi *et al.*, 2000). A common DM-GIS architecture is comprised of hand-held mobile computers and a cluster of remote backend servers storing the GIS database. The mobile computers, equipped with a GPS unit and cameras, communicate with the servers via wireless networks. Unlike a PDA, the database can be updated frequently with photographs captured by the cameras in the field. A DM-GIS will be invaluable for applications that require computation by field crews and/or fleets of vehicles. Examples of such applications include emergency services, utilities, transportation, rescue missions, telecommunications, scientific field studies, and environmental monitoring and planning (Karimi *et al.*, 2000). The most severe challenge to the implementation of a DM-GIS is the efficient checking of topology for the data in the database, and the reconciliation of topological inconsistencies when they occur.

Summary and Conclusions

The wide variety of approaches by which GPS is integrated with remote sensing and GIS is summarized in four models: linear, interactive, hierarchical, and complex. The linear model is the classic example of integration in which the unique strength of each discipline is utilized. Representing the ultimate integration, the complex model contains all possible interactions between any two components. This model may degenerate into one of the other three if some interaction is missing from the integration. Except in the complex model, GPS, which is used to collect point-based data for images and guide ground sampling, is considered less important than remote sensing and GIS. Remote sensing plays a more dominant role in the interactive model than in the linear one. Its importance exceeds that of a GIS in the hierarchical model. As the manner of integration becomes more complicated, it is increasingly difficult to rank the order of importance of each component in the integration.

This review has revealed that most of the integration cases fall into the linear model. That is, remotely sensed images that have been geo-referenced with GPS data are used to map resources and model environmental issues in a GIS. In the interactive model, the integration of remote sensing and GIS with GPS is less common than in the opposite direction, probably because GPS-guided data acquisition in the field is severely restricted by accessibility, a problem that may be overcome with the use of helicopters. Under the hierarchical model, there are only few application cases, all of which are restricted to environmental modeling and precision farming. Integration in the complex model has found applications in emergency response and mobile mapping.

In mapping natural resources, land-based resources such as farmland, vegetation, and forests have been studied extensively. Among environmental problems, the coastal zone has received the most attention. By comparison, hydrology, especially watershed and stormwater management, an area that can benefit considerably from the integrated approach, has received insufficient attention. Nor has landscape ecology. Although the integrated approach has been applied to hazardous environments, it has not been used to monitor and model natural hazards such as flooding, landslides, and volcanic eruptions. Thus, the full potential of integrating GPS with remote sensing and GIS has not yet been realized. Predictably, more research on the applications of integration to these areas will be carried out in the future.

The value of integrating GPS with remote sensing and GIS is the greatest in applications that require comprehensive, georeferenced, real-time or almost real-time data. These applications include mobile mapping, disaster mitigation, and emergency response. The future prospects for integrating GPS with remote sensing and GIS are in the development of enhanced location-aware multi-media PDA systems and distributed DM-GISs. Many new applications will become possible if the obstacles to integration and mobile communications are successfully tackled.

Acknowledgments

The author is indebted to three anonymous reviewers who made valuable comments regarding the previous version of the manuscript.

References

Ackermann, F., and H. Schade, 1993. Application of GPS for aerial triangulation, *Photogrammetric Engineering & Remote Sensing*, 59(11):1625–1632.

Adams, J.R., M.R. Gervais, and J.F. McLellan, 1990. GIS for dispatch automatic vehicle location and navigation systems, *Proceedings, GIS for the 1990s*, 05–08 March, Ottawa, Canada, pp. 1185–1196.

Albers, B.J., and C.B. Purdy, 1994. Spatial data technologies for environmental applications within the Department of Energy, *Earth Observation Magazine*, 3(12):18–22, 24.

Ambrosia, V.G., S.W. Buechel, J.A. Brass, J.R. Peterson, R.H. Davies, R.J. Kane, and S. Spain, 1998. An integration of remote sensing, GIS, and information distribution for wildfire detection and management, *Photogrammetric Engineering & Remote Sensing*, 64(10):977–985.

August, P., J. Michaud, C. Labash, and C. Smith, 1994. GPS for environmental applications: Accuracy and precision of locational data, *Photogrammetric Engineering & Remote Sensing*, 60(1):41–45.

Biggs, P.H., C.J. Pearce, and T.J. Westcott, 1989. GPS navigation for large-scale photography, *Photogrammetric Engineering & Remote Sensing*, 55(12):1737–1741.

Bock, Y., 1996. Introduction, *GPS for Geodesy* (A. Kleusberg and P.J.G. Teunissen, editors), Springer-Verlag, Berlin, Germany, pp. 3–36.

Bor, W.T., 1994. The use of GPS in GIS applications, *Journal of Geographical Science*, 17:77–85.

Burrough, P.A., and R.A. Mcdonnell, 1998. *Principles of Geographical Information Systems*, Oxford University Press, New York, N.Y., 333 p.

Campbell, J.B., 1996. *Introduction to Remote Sensing, Second Edition*, Taylor & Francis, London, U.K., 622 p.

Carstensen, L.W., Jr., 1998. GPS and GIS: Enhanced accuracy in map matching through effective filtering of autonomous GPS points, *Cartography and Geographic Information Systems*, 25(1):51–62.

Chen, X., D. Zhou, N. Zhou, and Z. Tan, 1997. Systematic analysis model for regional water resources based on a spatial information system, *Proceedings of International Symposium, Remote Sensing and Geographic Information Systems for Design and Operation of Water Resources Systems*, (M.F. Baumgartner, editor), Rabat, Morocco (IAHS Publication 242), pp. 43–51.

Clavet, D., M. Lasserre, and J. Pouliot, 1993. GPS control for 1:50 000-scale topographic mapping from satellite images, *Photogrammetric Engineering & Remote Sensing*, 59(1):107–111.

Clay, G.R., and S.E. Marsh, 1997. Spectral analysis for articulating scenic color changes in a coniferous landscape, *Photogrammetric Engineering & Remote Sensing*, 63(12):1353–1362.

Colomina, I., 1993. A note on the analytics of aerial triangulation with GPS aerial control, *Photogrammetric Engineering & Remote Sensing*, 59(1):1619–1624.

Colwell, R.N. (editor), 1983. *Manual of Remote Sensing, Second Edition*, American Society of Photogrammetry, Falls Church, Virginia, two volumes, 2440 p.

Cooper, R.D., T. Mccarthy, and J. Raper, 1995. Airborne videography and GPS, *Earth Observation Magazine*, 4(11):53–55.

Cowen, D., 1988. GIS vs CAD vs DBMS: What are the differences? *Photogrammetric Engineering & Remote Sensing*, 54:1551–1555.

Ehlers, M., G. Edwards, and Y. Bedard, 1989. Integration of remote sensing with geographic information system: A necessary evolution, *Photogrammetric Engineering & Remote Sensing*, 55(11):1619–1627.

Ehlers, M., D. Greenlee, T. Smith, and J. Star, 1991. Integration of remote sensing and GIS: Data and data access, *Photogrammetric Engineering & Remote Sensing*, 57(6):669–675.

Everitt, J.H., F.W. Judd, D.E. Escobar, and M.R. Davis, 1996. Integration of remote sensing and spatial information technologies for mapping black mangrove on the Texas gulf coast, *Journal of Coastal Research*, 12(1):64–69.

Fallas, G.J., and B. Savitsky, 1996. Land cover map of Costa Rica 1992: Application of remote sensing and geographical information systems, *Revista Geografica de America Central*, 32–33:131–142 (in Spanish with abstract in English).

Fernandez, A., P. Illera, and J.L. Casanova, 1997. Automatic mapping of surfaces affected by forest fires in Spain using AVHRR NDVI composite image data, *Remote Sensing of Environment*, 60(2):153–162.

Gao, J., 2001. Non-differential GPS as an alternative source of planimetric control for rectifying satellite imagery, *Photogrammetric Engineering & Remote Sensing*, 67(1):49–55.

Gao, J., and S.M.O'Leary, 1997. Estimation of suspended solids from aerial photographs in a GIS, *International Journal of Remote Sensing*, 18(10):2073–2085.

Goodchild, M.F., 1985. Geographic information systems in undergraduate geography: A contemporary dilemma, *The Operational Geographer*, 8:34–38.

Haack, B., J. Wolf, and R. English, 1998. Remote sensing change detection of irrigated agriculture in Afghanistan, *Geocarto International*, 13(2):65–76.

Hardisty, P.E., J. Watson, and S.D. Ross, 1996. A geomatics platform for groundwater resources assessment and management in the Hadramout-Masila region of Yemen, *Proceedings HydroGIS'96 Conference, Application of Geographic Information Systems in Hydrology and Water Resources Management*, 16–19 April, Vienna, Austria (IAHS Publication 235), pp. 527–533.

Hinto, J.C., 1996. GIS and remote sensing integration for environmental applications, *International Journal of Geographic Information Systems*, 10(7):877–890.

Ifft, T.H., W.L. Magette, and M.A. Bower, 1995. Nutrient management models combine GIS, GPS, and digital satellite imaging, *Geo Info Systems*, 5(7):48–50.

Joffe, B., 1994. Better and cheaper: technical innovation builds Palo Alto's high-quality map base, *Geo Info Systems*, 4(6):47–51.

Kane, B., and H.D.P. Ryan, III, 1998. Locating trees using a geographic information system and the global positioning system, *Journal of Arboriculture*, 24(3):135–143.

Karimi, H.A., P. Krishnamurthy, S. Banerjee, and P.K. Chrysanthis, 2000. Distributed mobile GIS: Challenges and architecture for integration of GIS, GPS, mobile computing and wireless communications, *Geomatics Info Magazine*, 14(9):80–83.

Lachapelle, G., M.E. Cannon, D.C. Penney, and T. Goddard, 1996. GIS/GPS facilitates precision farming, *GIS World*, 9(7):54–56.

Lachowski, H., P. Hardwick, R. Griffith, A. Parsons, and R. Warbington, 1997. Faster, better data for burned watersheds needing emergency rehab, *Journal of Forestry*, 95(6):4–8.

Li, R., 1997. Mobile mapping: An emerging technology for spatial data acquisition, *Photogrammetric Engineering & Remote Sensing*, 63(9):1085–1092.

Lillesand, T.M., and R.W. Kiefer, 1994. *Remote Sensing and Image Interpretation, Third Edition*, Wiley & Sons, New York, N.Y., 750 p.

Lunetta, R.S., R.G. Congalton, L.K. Fenstermaker, J.R. Jensen, K.C. Mcgwire, and L.R. Tinney, 1991. Remote sensing and geographic information system data integration: Error sources and research issues, *Photogrammetric Engineering & Remote Sensing*, 57(6):677–687.

McCormick, C.M., 1999. Mapping exotic vegetation in the Everglades from large-scale aerial photographs, *Photogrammetric Engineering & Remote Sensing*, 65(2):179–184.

McGregor, S.J., 1998. An integrated geographic information system approach for modeling the suitability of conifer habitat in an alpine environment, *Geomorphology*, 21(3–4):265-280.

Monday, H.M., J.S. Urban, D. Mulawa, and C.A. Benkelman, 1994. City of Irving utilizes high resolution multispectral imagery for NPDES compliance, *Photogrammetric Engineering & Remote Sensing*, 60(4):411–416.

Murakami, E., and D.P. Wagner, 1999. Can using Global Positioning System (GPS) improve trip reporting? *Transportation Research Part C: Emerging Technologies*, 7(2–3):149–65.

Novak, K., 1993. Data collection for multi-media GIS using mobile mapping systems, *Geodetical Info Magazine*, 7(10):30–32.

———, 1995. Mobile mapping technology for GIS data collection, *Photogrammetric Engineering & Remote Sensing*, 61(5):493–501.

Runyon, J., 1994. Environmental management solutions for agriculture: Integrating field inspections, GIS, GPS, and aerial photography, *Geo Info Systems*, 4(4):42–44.

Runyon, T., R. Hammitt, and R. Lindquist, 1994. Buried danger: Integrating GIS and GPS to identify radiologically contaminated sites, *Geo Info Systems*, 4(8):28–36.

Sigrist, P., P. Coppin, and M. Hermy, 1999. Impact of forest canopy on quality and accuracy of GPS measurements, *International Journal of Remote Sensing*, 20(18):3595–3610.

Stephens, P.R., 1991. Remote sensing and geographic information systems for resource management and environmental monitoring, *Asian-Pacific Remote Sensing Journal*, 3(2):69–73.

Sugumaran, R., C. Davis, J. Meyer, T. Prato, and C. Fulcher, 2000. Web-based decision support tool for floodplain management using high-resolution DEM, *Photogrammetric Engineering & Remote Sensing*, 66(10):1261–1265.

Swindell, J., 1995. A rich harvest: Integrating GPS and GIS on the farm, *Mapping Awareness*, 9(1):32–35.

Tao, C.V., 2000. Semi-automated object measurement using multiple-image matching from mobile mapping image sequences, *Photogrammetric Engineering & Remote Sensing*, 66(12):1477–1485.

Thomas, M., 1997. DIY remote sensing, *Mapping Awareness*, 11(1):32–33.

Treitz, P.M., P.J. Howarth, and P. Gong, 1992. Application of satellite and GIS technologies for land-cover and land-use mapping at the rural-urban fringe: A case study, *Photogrammetric Engineering & Remote Sensing*, 58(4):439–448.

Usery, E.L., S. Pocknee, and B. Boydell, 1995. Precision farming data management using geographic information systems, *Photogrammetric Engineering & Remote Sensing*, 61(11):1383–1391.

Van Essen, R.J., and I.A. De Taeye, 1993. The road map redefined: The European digital road map triggered by car information systems, *Geodetical Info Magazine*, 7(9):32–34.

Walter, L.S., 1990. The uses of satellite technology in disaster management, *Disasters*, 14(1):20–35.

Welch, R., M. Remillard, and J. Alberts, 1991. Integrated resource databases for coastal management, *GIS World*, 4(3):86–89.

———, 1992. Integration of GPS, remote sensing, and GIS techniques for coastal resource management, *Photogrammetric Engineering & Remote Sensing*, 58(11):1571–1578.

Welch, R., M. Remillard, and R.F. Doren, 1995. GIS database development for south Florida's national parks and preserves, *Photogrammetric Engineering & Remote Sensing*, 61(11):1371–1381.

Wilkinson, G.G., 1996. A review of current issues in the integration of GIS and remote sensing data, *International Journal of Geographical Information System*, 10(1):87–101.

Wooden, W.H., 1985. Navstar Global Positioning System: 1985, *Proceedings of the First International Symposium on Precise Positioning with the Global Positioning System*, 15–19 April, Rockville, Maryland, 1:23–32.

(Received 03 January 2001; revised and accepted 10 October 2001)