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Remote Sensing Tools Assist in Environmental Forensics: Part II—Digital Tools

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This is the second part of a two-part discussion, in which we will provide an overview of the use of GIS and GPS in environmental analysis and enforcement. Geographic Information Systems (GIS) describes a system which manages, analyses and displays geographic information. Environmental applications include analysis of source, extent and transport of contaminants, nonpoint runoff modeling, flood control, and emergency response support. The ability to examine spatial relationships between environmental observations and other mapped and historical information, and to communicate these relationships to others, makes GIS valuable in environmental forensics. The US Environmental Protection Agency currently requires the inclusion of locational information with all other environmental data that is collected. Geographic Information Systems is a complex tool that requires careful planning and design to be successfully implemented. Choices in hardware, software and data development must be based on evaluation of project objectives, analytical requirements, data availability and data development considerations. Data sets must be evaluated and documented with metadata. The Global Positioning System (GPS) is a satellite-based system which provides highly accurate, three-dimensional position information anywhere on the earth's surface. Using portable radio receivers, field analysts can easily record the positions of spill sites, sampling locations and other environmental features. Spatial accuracy of GPS ranges from 20–30 m (single receiver) to 1–5 m (differential GPS) for navigation-grade instruments, and down to millimeter level accuracy for geodetic units. Global Position Systems can be used not only to capture spatial information into a GIS system, but also to evaluate and quantify the spatial accuracy of existing digital map data, and to provide control points for existing aerial photographs and other remotely-sensed data.

Introduction

Part I of this two-part series discussed the application of traditional remote sensing techniques in environmental forensics (Brilis, Gerlach and van Waasbergen, 2000). The traditional techniques focused on mapping and aerial photography. Prior to the introduction of computers, aerial photographs were acquired, processed, and interpreted manually and/or by mechanical devices. Application of maps and aerial photography has been a valuable tool for environmental forensics. The introduction and proliferation of computers in the field of remote sensing, in addition to satellites, has changed the way data is acquired, processed, and analysed. A more in-depth look at aerial photography is described by Grip, Grip and Morrison (2000).

The use of Geographic Information Systems (GIS) as a tool in environmental forensics is increasing. Geographic Information Systems are systems where geographic data describing features on the earth's surface are managed, displayed, manipulated, and analysed (USEPA, 1992a). Digital remote sensing and the use of GIS make it possible to rapidly collect and analyse spatial data, yielding a powerful set of tools for the analysis of the source, extent, and transport of various types of contamination.

The ability to analyse complex, spatial data makes GIS technology interesting to a growing number of users within the environmental sciences community. Applications include environmental monitoring and analysis, modeling nonpoint runoff, landscape ecology, flood control modeling, enforcement actions, and

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emergency response support. The U.S. Environmental Protection Agency (EPA) is tapping into the many capabilities of GIS technology as it continues its long-term evaluation of ecological trends.

Recognizing the critical role of geographic data, EPA created the Locational Data Policy (LDP) in 1991. This policy establishes the principles for collecting and documenting latitude/longitude coordinates for facilities, sites and monitoring and observation points regulated or tracked under Federal environmental programs within the jurisdiction of the EPA. The intent of the LDP is to extend environmental analyses and allow data to be integrated based upon location, thereby promoting the enhanced use of EPA's extensive data resources for cross-media environmental analyses and management decisions. This policy underscores EPA's commitment to establishing the data infrastructure necessary to enable data sharing and secondary data use. The EPA accuracy goal has been established at 25 m and the best method currently available to satisfy the requirements of LDP is currently considered to be GPS (Geospatial Metadata, 1997). Since the finalization of LDP, technology has enabled a 2–5-m accuracy using simple hand-held devices and differential error-correction, and sub-meter accuracy with more sensitive units.

The heavy emphasis on analytical manipulation of spatial data is the main characteristic that distinguishes GIS from other technologies like computer-aided design and electronic mapping systems. Using GIS, a forensic scientist is able to present a complete picture of a site location, tiering maps of streams, geopolitical boundaries, transportation routes, topography, and examine the spatial relationships between them. In addition, GIS display tools allow these relationships to be communicated to others in a meaningful way.

Geographic Information Systems are used to organize field data in a spatial context that can allow decision makers to make more informed choices as the study progresses. There is a growing need for spatial analysis to be an integral part of routine data analysis and decision-making. To meet this need, GIS technology is migrating to the desktops of applied technologists in fields like biology, economics, and environmental science.

The current trend is to combine GIS technology with Internet applications to build distributed spatial databases and to provide GIS tools to users anywhere in an organization, or even in the field. Distributed spatial databases can be more reliably maintained, because each contributor can focus on the data sets with which they have the most expertise. Development of uniform standards for spatial data formats and quality will make it possible for GIS users to more confidently draw on data sets that are built and maintained by others, without a need to acquire, convert and maintain it themselves.

Technique and Scope

The power of GIS to generate highly specialized informational maps makes it an effective method for presenting information to decision makers, the public, and potentially in the courtroom. But GIS is capable of much more than generating maps and presenting data. Environmental forensic studies can produce complex data that are difficult to represent verbally or sometimes even visually. Using GIS, forensic investigators are able to interpret spatial data, manage complex databases, and use layers of information from various sources. Based on GIS, investigators can produce a realistic and understandable visual analysis of a case. Some common analysis capabilities include measurements (spatial extent and volumes of mapped features), attribute reclassification (combining information from different data layers to determine, for example, the soil types in land parcels owned by different people), topological overlay (to determine common boundaries or subdivide existing map units based on features in other layers), connectivity operations (to determine the shortest route along a network, for example), coordinate transformations (to bring different data sets into a common spatial coordinate system so they can be overlain), and surface analysis.

One example of how GIS analyses were used in environmental forensics was a case in which EPA assessed a number of mining companies for environmental damages that resulted from lead-zinc mining in southwestern Missouri. Site investigations and photo interpretation were used to map the distribution and extent of hazardous mine waste. This was combined with historic lease and ownership information to determine the extent to which each company should be held liable for cleanup. In one instance, the allocation was further refined by the use of historic air photos: by measuring changes in extent and volume of mine tailings on air photos over several years, the amounts of waste produced during the stewardship of a specific company could be determined. This allowed the cost allocation for that company to be adjusted to more accurately reflect their contribution to the problem.

Another application is used to support Section 404 of the Clean Water Act (CWA) enforcement investigations. Section 404 outlines the procedures and requirements for obtaining federal permits prior to the discharge of dredged or fill material into Waters of the United States including wetland areas. These investigations utilize the interpretation of historical and current aerial photography to document the locations of historical wetland areas relative to current site conditions. Aerial photography is obtained, scanned and geo-referenced to a known coordinate system using Digital Ortho Quarter Quadrangles (DOQQs) produced by the United States Geological Survey. Digital Ortho Quarter Quadrangles are map accurate images in which every pixel, or picture element, has a known coordinate value. Through the geo-referencing process, these coordinate values are transferred to the historical aerial photography. Once all the aerial photography is projected in the same coordinate system then features or conditions observed on one date can be easily transferred and overlayed on each date of photography.

This procedure enables historical wetland boundaries to be transferred to current aerial photography which dramatically showed in one recent case: residential roads, lots, and storm water lakes located in former wetland areas. The picture this presented was influential in convincing the jury that wetlands had been filled without a permit. The dramatic presentation of "before and after" aerial photography coupled with the ability to accurately geo-reference and overlay features of interest provides strong visual evidence of changes on a site over time. This technique has been used successfully on a number of enforcement investigations across EPA Regions.

Planning a GIS Project

Planning is an important step in a forensic investigation. Geographic Information Systems is a complex tool that requires planning in many areas to avoid problems that can affect the project's outcome. Scientists have identified six areas essential to the GIS project planning life cycle. They are to define project objectives, identify analytical requirements, define data and hardware requirements, determine data availability, resolve data development issues and implement project plans.

As with any analytical process, the quality of the result is dependent upon the recognition of the exact problem and the implementation of the correct steps in addressing it.

Project Objectives

Defining specific project objectives reduces wasted time and effort in the project planning life cycle. Project objectives should encompass every aspect of the project, from data collection and manipulation to data display and archival storage. Not all aspects of a project are known in their entirety at the onset of a project, of course, so project objectives should be flexible enough to be customized as more knowledge related to the study becomes available. Sometimes very little is known about the project at the beginning of the study and a preplanning data gathering effort is necessary to establish the facts.

Analytical Requirements

The next step in planning is the identification of analytical requirements. The defined analytical requirement will be used to specify more exact standards for database data quality, resolution, and scale. This stage of the GIS planning process requires the input of project staff and GIS specialists. It is important that the project staff communicate their exact needs to the GIS experts. After the requirements are established, program management staff should prioritize the needs and establish measurable data quality objectives to meet them.

At this stage it is useful to consider the attribute information required for analysis, minimum data resolution and scale, and data input and output formats. Data visualization is affected by the sensitivity and resolution of graphics terminals and printers.

Data Availability

The project's analysis objectives can only be met if the data are available. The degree to which GIS data are available is related to the resolution, scale, and compilation date required by the study. Another availability factor is cost. Data may be available in the sense of existing but may be beyond the cost restrictions of the particular project. The data needed for a project will fall into one of three categories: data that already exists and is available at no cost or may even be supplied with the GIS software; data that must be purchased from a vendor; and data generated specifically for the project at hand.

Data Development Issues

Data development may be required to address the data quality objectives of the project. At this point, data must be assessed to ascertain their adequacy. Project deadlines and data quality objectives (DQOs) should be reviewed at this time. The personnel responsible for critical decisions should be involved in this adequacy review. Key questions should be asked. Are the data adequate to meet the DQOs of the project? Can defensible decisions be made based on the data at hand? Is the data quality sufficient? Is there enough time to gather additional data if necessary?

In any one project, there are generally three types of spatial data sets:

(1) Contextual data. These are used on maps primarily to provide a common reference, but are not used for analysis or modeling. Examples of contextual data include state and county boundaries, oilfield boundaries, major highways or other landmarks. Most often, this is data that may be supplied by a GIS software vendor.
(2) Relevant basemap data. These are commonly obtainable data sets that may be relevant to the environmental issues and may be used for analysis or modeling. Examples include topography, street networks, hydrography, soil and land-use data, known sewage outfalls, and historical air photos. Typically, this is data that must be purchased from a vendor.
(3) Specific project data. These are the data that are unique to the project at hand, and may include sampling locations, results of site investigations, monitoring well data, new air photos, and facility plans. At the beginning of a project, this will be the data generated specifically for the project at hand.

Of these three categories, the contextual data are usually the easiest to obtain, and has the fewest quality requirements. The basemap data are often also easy to obtain, but great care must be taken to ascertain the quality of these data sets, and to understand the limits of their use in spatial analyses or modeling. Specific project data are generally the category over which one has the most control, but which also require the most effort and careful planning to obtain.

Digitized data and the informational maps that result from GIS applications are only as reliable as the quality of the data that is input. Whenever GIS is used for decision-making, it is important to state the confidence levels of the information. Some research effort is under way to represent the reliability of the data by subtle differences in the display characteristics.

All aspects of the information should be evaluated for cost impact. Cost considerations may include the acquisition of data, travel costs, quality assurance, contractor fees, and all project management costs.

Metadata

Metadata is data about data and consists of information that characterizes data. Metadata are used to provide documentation for data products. In essence, metadata answer who, what, when, where, why, and how about every facet of the data that are being documented. For remote sensing tools, metadata includes (Geospatial Metadata, 1997):

Identification information

Basic information about the data set. Examples include title, geographic area covered, currentness, and rules for acquiring or using the data.

Data quality information

An assessment of the quality of the data set. Examples include positional and attribute accuracy, completeness, consistency, sources of information, and methods used to produce the data.

Spatial data organization information

Describes the mechanism used to represent spatial information in the data set. Examples include the method used to represent spatial positions directly (such as raster or vector) and indirectly (such as street addresses or county codes) and the number of spatial objects in the data set.

Spatial reference information

A description of the reference frame for, and means of encoding, coordinates in the data set. Examples include the names of and parameters for map projections or grid coordinate systems, horizontal and vertical datums, and the coordinate system resolution.

Entity and attribute information

Describes information about the content of the data set, including the entity types and their attributes and the domains from which attribute values may be assigned. Examples include the names and definitions of features, attributes, and attribute values.

Distribution information

Offers information about obtaining the data set. Examples include a contact for the distributor, available formats, information about how to obtain data sets online or on physical media (such as cartridge tape or CD-ROM), and fees for the data.

Metadata reference information

This provides information on the currentness of the metadata information and the responsible party. The standard has sections that specify contact information for organizations or individuals that developed or distribute the data set, temporal information for time periods covered by the data set, and citation information for the data set and information sources from which the data were derived.

The standard for how metadata information is organized in a computer system or in a data transfer, or by which this information is transmitted or communicated to the user are not yet defined. Additional information about metadata is available from the Federal Geographic Data Committee (FGDC) http://www.fgdc.gov

Implementation

The GIS project implementation phase carries out the database development and analysis objectives. The database design defines the database structure, its characteristics, coverage attribute coding scheme, data models, and automation methods. The resulting design document should determine if the GIS database meets the project's analytical objectives. The data capture and automation phase carries out the database design through data acquisition and integration of data into the GIS system. The database design includes digitizing analog maps, converting digital data into GIS format, and correcting and coding data.

Once the database is complete, the GIS analysis functions are tested. When the staff are satisfied with the system's ability to meet the analytical requirements of the project, database production can begin.

GIS User Interface

Geographical Information Systems rely on a relational database management system to provide the ability to query, manipulate, and extract geographic reference and attribute data. This approach permits standard statistical manipulations of attribute data, as well as logical and boolean queries based on GIS feature characteristics (USEPA, 1992a). Most GIS software packages provide a generic tool set to perform spatial analysis operations, database operations, data management tasks, and data reporting/mapmaking tasks. The generic tools can then be modified to suit the needs of the organization, group, or individual user. Such custom GIS applications can be built to simplify complex tasks, automate data capture and data entry, and provide decision support tools to novice users. Automation and data-validation save time and can prevent many errors.

Geographic Information Systems And Remote Sensing

> Remote sensing data, from vegetation and climatic data to outlines of manmade structures, can form much of the information that is entered into a GIS. The technologies of remote sensing and GIS are distinct, but complimentary. Different equipment and technical skills are needed for each, but in both cases the user must have a string grasp on the information that is collected, be it forestry, geology, man-made structures, etc. Remote sensing technology focuses on sensor systems and image processing, whereas GIS requires expertise with the principles of spatial analysis, map projections and databases. (Aronoff, 1995)

Geographic Information Systems and remote sensing are both used in environmental forensics. Remote sensing analyses are supported by other data stored in a GIS, and GIS applications will be improved by remotely sensed data. The availability of information that only remote sensing can provide, combined with the powerful tool and technology of GIS, enable a forensic scientist to more efficiently and effectively conduct an environmental investigation.

Global Positioning System Technology

Global positioning system (GPS) technology is a satellite-based radio positioning and time-transfer system that can provide accurate, three-dimensional geographic positioning anywhere on the earth's surface. Developed by the U.S. Department of Defense, this technology was designed primarily for military navigational systems, but there are numerous geocoding applications in the field of environmental science. Global Positioning Systems has become a standard technology in geodesy, geography, surveying, and environmental monitoring and analysis.

The Science of Satellite Positioning

By using radio signals from a constellation of earth orbiting satellites, earth based receivers can compute highly accurate three dimensional geographic coordinate positions.

If data on the satellite geometry, position, and movement (called ephemeral data) are known, the distance to an earth based receiver can be geometrically calculated by measuring the time it takes for the radio signals from four separate satellites to reach the receiver. This type of positioning is only possible because of the accuracy and speed of modern clocks and computers. Ephemeral data are constantly monitored by a network of earth tracking stations and relayed back to the satellite where they are included in the transmitting signal and tracked by the GPS receiver. The GPS system consists of 28 satellites in 12-h polar orbits at 12,000 miles above the Earth's surface (EPA, 1999b). This is sufficient to allow at least four satellites to be available in any location at any time. The satellites transmit a sequence of pseudo-random binary values (zeros and ones) that repeat over a specific time interval. The receiver determines the offset in time between the received codes and the expected codes over the same time interval, and converts this to the distance (pseudorange) to the satellite. If this ranging process is repeated constantly from at least three satellites, and known errors caused by clock timing and atmospheric effects are modeled, a precise position can be calculated and referenced to a known datum and coordinate system. Because the receivers (which can be small, inexpensive hand-held devices) do not have the same extremely accurate time-keeping systems as the satellites, the fourth necessary element, time, can be determined by using a fourth satellite signal. In addition to the ranging codes, the satellites also regularly transmit corrections for their predicted positions. These corrections are determined by the GPS ground stations around the world, which monitor any drift that may occur in the satellites' orbits.

An important limitation of the GPS system is that it uses very weak radio signals. This means GPS receivers require unobstructed lines-of-sight to the satellites, and they will generally not work inside buildings, or even under trees or in "urban canyons" (city streets surrounded by tall buildings). Using larger antennae, such as those on backpack mounted units, some forest-canopies or other low-impedance obstructions can be tolerated.

How accurate is GPS?

Accuracy depends on several factors including the design of the receiver. There are two general classes of GPS receivers: navigation and geodetic. Navigation grade instruments use only the ranging-codes to determine positions, and can routinely yield accuracies in the 2–5 m range. The geodetic quality units can compute coordinates with millimeter level accuracy, by using not only the ranging codes, but by also measuring the phase-offset between the internally generated signal and the carrier wave of the satellite signal. Geodetic GPS measurements require careful acquisition of the GPS signals over a fairly long time interval (in the order of 15 min), making it unsuitable for many survey applications.

In the recent past the GPS signals that are available to general public (C/A-code) contained an artificial error of up to 100 m that is added by the US Military for security reasons. This is known as "Selective Availability (SA)". A single GPS unit is therefore only accurate to about 100 m. Using two units, one stationary, over a known geodetic control point, and one mobile, the Selective Availability can be removed either in real time, through direct communication between the two units, or after the survey during post-processing of the data, this is known as differential correction. However, as of 1 May 2000, under the direction of President Clinton, the US military stopped the intentional degradation of the GPS signal. With SA "turned off" civilian users of GPS will be able to pinpoint locations up to 10 times more accurately than before (White House, 2000a). For standard GPS units not using differential correction techniques, this means positional accuracies between 20 and 30 m will be possible (White House, 2000b). Even with the turning off of SA, positional accuracy will be superior using differentially corrected GPS data. With this post processing technique (or in realtime with DGPS Units) positional accuracy between 1 and 5 m is possible. Which type of data are best for a given application depends on the spatial sensitivity of the data. For example, the location of a water quality sample point 10 miles off shore may be reasonably located using a standard GPS unit with 20–30 m accuracy. If the sample point is located well within the boundaries of a homogeneous cover type or land form then the 20–30-m accuracy may be sufficient. However, if the sample point needs to be spatially distinguished from other close-by sample points, DGPS is required.

Applications

Apart from the traditional types of geocoding, surveying, and the collection of accurate latitude/longitude coordinates, one of the main applications of this technology is in the area of GIS. Global Positioning System technology provides a means of evaluating and quantifying the spatial accuracy of digital map data as well as creating digital cartographic data structures. Potential products and application areas include direct digital mapping and field navigation.

In direct digital mapping portable GPSs can be hand carried or mounted on vehicles to create digital data structures that can be used as direct input into GIS systems. The system is used to update existing map data, provide highly accurate subsections, or create entirely new map products.

In field navigation, field sampling teams can use GPS to easily and accurately record the location of specific sampling locations or to navigate back to a previous sampling point even when surface markers have been disturbed or are no longer present.

One application integrating GPS data into GIS data bases involves, once again, the investigation of Section 404 of the CWA violations. Already mentioned in this paper is the geo-referencing of sets of current and historical aerial photography covering and area under investigation. This process establishes coordinate values for each pixel in each photograph. The GPS receiver can record coordinate values at sample points or along boundaries of features of interest. Once these coordinate values are recorded they can be downloaded and automatically overlayed on the geo-referenced aerial photography. This allows the analyst to apply the attributes determined in the field to the signatures seen on the aerial photography (for example, soils moisture conditions, vegetation community composition, or the outlines of fill areas or structures). In addition, changes to the site or changes in the locations of features relative to their historic conditions as depicted on the aerial photography will be apparent using this overlay technique.

Sample points can also be plotted on the aerial photography to show the spatial arrangement over the site and to determine if adequate spatial coverage was obtained during a survey. With new GIS/GPS interfaces this can be done in near realtime using a laptop in the field. Additional sample points can then be taken as necessary. On one recent investigation it was determined, after review of the GPS sample point locations, that additional sample points were required to give better spatial coverage and the field work was adjusted accordingly.

The GPS data, whether sample point locations or the boundaries of significant environmental features or conditions, are stored in a GIS for later analysis and presentation. Large format thematic maps or digital aerial photos can be plotted along with the geo-referenced sample point locations and features of interest.

Quality control

A carefully planned GPS survey can provide first order control locations which can then be utilized to assess the spatial quality of other thematic overlays that have been developed for the database or to georeference raw data layers, such as satellite or aerial images.

Network modeling

Kinematic (mobile) positioning techniques can be used to create network structures with much greater accuracy and precision than is currently possible. Spatial variations in movement and rate, and time series analysis can be acquired at greater data resolutions.

Photogrammetry QA

Photogrammetry and cartography often remain the most cost effective methods of creating thematic maps. The ease of establishing a control configuration for existing aerial photographs with GPS technology as opposed to traditional surveying methods can result in significant savings in cost, time, and manpower.

Future Directions in Handling Spatial Information

Spatial information technology is still rapidly developing. Current trends show a convergence of GIS and navigation components into many aspects of business and even everyday life. Geographic Information System software is evolving from large, proprietary systems to modular, component-based systems that provide specific functionality. Common business productivity software can now be enhanced with these GIS components, putting spatial analysis tools in the hands of any user. Common standards for the development and maintenance of GIS data are being developed and are increasingly supported by the major software developers. GPS receivers have become more ubiquitous, and are being integrated into wireless telephones, automobiles, computers and other appliances. Finally, the accessibility of GIS data and functionality through the Internet will mean that information from almost any environmental project can be quickly integrated into a GIS database and made available for use by all participants, wherever they may be.

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Notice

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