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Tripcevich, Nicholas

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Flexibility by Design: How Mobile GIS Meets the Needs of Archaeological Survey

Nicholas Tripcevich

ABSTRACT: Handheld computers have become capable of more than data storage and precision measurement; they have begun to contribute to scientific studies conducted in demanding field research settings. Recent versions of mobile GIS software allow researchers with limited programming skills to tailor the software to the priorities and theoretical needs of individual research projects. Depending on the research needs in a given situation, data recording can be expedient or thorough, and data acquisition forms can be designed to emphasize flexibility for varied or unpredictable field conditions. By giving researchers access to large digital datasets and spatial analysis tools while in the field, mobile GIS facilitates the data acquisition process and can contribute to the quality and the efficiency of fieldwork. In this study, the implementation of ESRI Arcpad 6 in a high-altitude archaeological survey project in Peru presented challenges to the mobile GIS system that are perhaps common to many mobile GIS-based scientific fieldwork projects. The paper discusses the benefits and the limitations of doing an archaeological survey using mobile GIS. It also considers some of the ways in which improvements in mobile GIS technology will facilitate the methods of resource managers and field scientists in the future.

KEYWORDS: Mobile mapping systems, rugged field GIS, archaeological survey

Introduction

If mobile geographical information systems are to advance the methods of scientific field studies and resource management, the equipment must do more than merely improve the way in which data are stored and retrieved in the outdoors. Fieldwork applications require flexible and easily customizable interface designs in order to permit more rapid attribution of Geographic Information Science (GIS) data and to encourage the deployment of new tools for fieldwork in remote research situations. When researchers and managers can customize their software without being computer programmers, they can personally design a user interface for their research equipment that prioritizes aspects of fieldwork that are important to the theoretical goals of the project.

This paper describes mobile GIS strategies developed for an archaeological survey conducted in the Peruvian Andes near a high-altitude source of obsidian.¹ The research involved reconnaissance and rapid recording of spatial distributions of surface artifacts, as well as limited sampling and test excavations at archaeological sites. When the survey team encountered archaeological phenomena, the features were recorded using a mobile GIS

Nicholas Tripcevich, Department of Anthropology, University of California, Santa Barbara, Santa Barbara, CA 93106. E-mail: <nico@umail.ucsb.edu>. [<http://titicaca.ucsb.edu/colca>.]

consisting of a Pocket PC running ESRI Arcpad 6 with an external Trimble Pocket GPS (Figure 1). In addition, the team had a pair of older Trimble GeoExplorer GPS units running continually along the edge of each survey line to map the extent of all surveyed areas.

The mobile GIS equipment permitted the survey team to record archaeological distributions below the scale of the "archaeological site" by documenting concentrations of like artifacts using polygon geometry. The resulting dataset consisted primarily of artifact loci delimited using polygons throughout the survey area where each cluster roughly corresponded to the traditional "archaeological site." Each artifact locus contained a significant amount of variability inside the polygon, so the features were described in terms of estimates of their dominant and secondary components, as determined by the archaeologists reviewing the site. There was insufficient time for sampling at every artifact concentration, and therefore component probabilities were estimated rapidly by fieldworkers according to the priorities of the research. When high-speed feature recording is a priority, and if individual components of the study are intermingled and

¹ Obsidian is a volcanic stone used in antiquity for making tools.

cannot be mapped independently, field mapping may benefit from this approach.

Over the past several decades, GIS technology has enhanced the data management and spatial analysis capabilities of research in laboratory settings. In contrast, data-acquisition equipment among the sciences with a fieldwork component, such as geography, geology, biology, and archaeology, have yet to be similarly advanced. The Global Positioning System (GPS) has revolutionized the process of gathering new, spatially located data, but it remains a one-directional acquisition process with limited field access to previously gathered datasets. For the crucial step of attributing spatial data there are few options for most users besides the rudimentary GPS data dictionary approach which makes it possible to gather attributes for anticipated data types in a consistent way by creating pre-defined templates prior to fieldwork.

In addition to facilitating the recording and attributing of phenomena, mobile GIS can empower researchers by providing access to statistical tools while still in the field. This will transform the methodology of field research in many disciplines such that researchers will be able to graphically explore, summarize, and compare their data in the field, and thereby improve the practice of their fieldwork in an iterative manner. Mobile GIS can also function as a digital data retrieval and display device that is versatile and multi-scaled. Improvements in the quality of automated cartography and labeling, along with further hardware enhancements, are leading to automated map displays that are aesthetically comparable to paper maps. Many field projects will benefit from the ability to bring their large digital datasets with them into the field. A mobile GIS is the perfect context in which to explore and query existing data while in the field, error-check the data, and contribute new entries to the dataset. A project organized around mobile GIS units can accommodate the recent increase in complex digital data gathered during fieldwork, such as GPS information and digital photography, while simultaneously making available pre-existing digital datasets to fieldworkers. This eases the link between fieldwork and field collection of lab samples and facilitates more rapid analysis and dissemination of findings from new data.

Despite the potential of these technologies there are numerous obstacles to using mobile GIS in rough fieldwork conditions. Each piece of equipment requires care, battery life is a constant concern, and data management responsibilities become more complex. Technical support services are usually far away from the field site, and so mo-

bile GIS designs must be robust. Furthermore, a knowledge gap inevitably grows during the course of the field season between the mobile GIS users who control the database, and the rest of the team who get information secondhand. Given the current technology, mobile GIS should be considered for research projects with a spatial component, that are situated in environments where GPS reception is adequate, and for projects where GIS is already in use for other aspects of the research project.

The discussion will explore the application of mobile GIS to archaeological survey by first describing archaeological survey and some of the principal issues and goals of field survey. Next, an explanation of the mobile GIS approach will describe the preliminary preparation for fieldwork, the implementation of the mobile GIS, and associated complexities. A discussion of the implications of mobile GIS for archaeological research, and for scientific fieldwork more generally, concludes the article.

Mobile GIS and Archaeological Survey

Whether excavating buried settlements or combing the land surface through systematic survey, archaeological investigations require extensive spatial data management. Over the past two decades GIS has proven valuable in a number of archaeological applications (Aldenderfer and Maschner 1996; Allen et al. 1990; Kvamme 1999; Maschner 1996; Wheatley and Gillings 2002). The new technology has proved useful for managing spatial data, and various approaches to the analysis and modeling of archaeological problems are being explored with GIS. There are added challenges, however, because, as many are finding, the conventional ways of organizing archaeological data do not always lend themselves to a GIS-based data structure. For example, archaeologists commonly use descriptive and qualitative typological categories, they must cope with very small sample sizes that require conditional analytical treatment, and during fieldwork they often record a wide variety of phenomena depending on what is encountered. Archaeological research provides a good test of the capabilities of mobile GIS because the data are complex, the field conditions are generally rigorous, and the GIS needs to have an accessible interface in order to be learned by a research team.

The Upper Colca Archaeological Research Project [<http://titicaca.ucsb.edu/colca/>] in highland Peru,

is a regional survey project focusing on the area surrounding a major obsidian source in the south-central Andes (Brooks et al. 1997; Burger et al. 1998). The obsidian source is located in a caldera at 4900 meters above sea level (16,000 feet), and fieldwork required camping out for five to ten days at a time, in a trying environment for people and electronics alike. The field season consisted of archaeological survey and excavations of numerous one-square-meter test pits at three sites in the area. The theoretical focus was on documenting differences in the surface concentrations of lithic chipping debris found throughout the region. These concentrations are the result of obsidian processing activities in the Colca Valley near the geological obsidian source, a resource that was of regional importance during pre-Hispanic times.

Archaeological fieldwork is often considered in two broad categories: *survey*, or an evaluation of artifact distributions on the surface of an entire region; and *excavation*, where an individual site is investigated in detail over a period of weeks, months, or years. This project was primarily a surface survey, where the spatial accuracy of current GPS and GIS technology proved to be sufficient to map archaeological distributions at a much finer resolution and level of detail than was feasible without the use of a mobile GIS.

Related Research

Field computer interfaces tailored for specific research projects are becoming increasingly common as software interfaces are designed to be customizable. With the availability of commercial mobile GIS products such as ESRI's Arcpad, research projects are commonly using mobile software out of the box to supplement existing field methods. Researchers are also developing models that interact with mobile GIS units in ways that improve field data acquisition. In the late 1990s, a project by a computer science team at the University of Kent, U.K., led by archaeologist Nick Ryan developed a "context aware" software package for handheld computers maintaining both spatial and temporal data as well as image data and notes collected during fieldwork (Ryan et al. 1998). The system was designed to respond to the "context" of the user—which might include spatial location, time of day, temperature, or combinations of the above. Based on behavior models, such a system could perhaps alert a wildlife biologist that he or she is approaching a context in which a particular species of animal might be encountered.

Recent work by Hardy Pundt (2002) describes data quality improvement for field research with mobile GIS through links to external semantic plausibility models. These controls can use logical rules to guide data entry so that, for example, an archaeological site with ceramic artifacts must have some occupation periods that are not from the "Pre-ceramic Period." The site must include dates that occur after the accepted start date for ceramics use in the region, or there is a logical error. Warnings from logic-based error checking could significantly reduce simple mistakes in field recording. This and other model-based interfaces are useful additions to field research equipment; however, in the archaeological study described below the emphasis was on designing for flexibility in data attribution during fieldwork.

Mobile GIS and Surface Archaeology

The typical archaeological survey consists of a group of archaeologists systematically walking transects across an unstudied area in order to evaluate the distributions of archaeological materials in the region (Banning 2002). A survey team might consist of five archaeologists spaced at 15-meter intervals along a survey line, walking parallel transects (see Figure 2). When an area with a density of archaeological materials meeting the defined criteria of an "archaeological site" is found, the concentration is evaluated and recorded by the survey crew as rapidly as possible so that the team can return to covering ground with pedestrian transects. Traditional recording methods involve describing the site in a field notebook, filling in forms on a clipboard, taking photographs, and locating the site on a topographic map as accurately as possible. Archaeologists have almost universally replaced this last step by noting GPS coordinates for the site.

Current mobile GIS technology contributes to this method in several ways. First, mobile GIS aids surveyors with navigation because the anticipated survey transects, and some other relevant guidance information, can be clearly indicated in conjunction with the current GPS location. Second, mobile GIS allows researchers to record new vector data along with attribute forms that are more flexible than those provided by GPS, or by data dictionary approaches in the past. Finally, mobile GIS allows researchers to transport digital datasets into the field so that they can do error checking immediately, review the work of other research

Figure 1. Mobile GIS implementation with ESRI Arcpad 6. New data sources from external instruments are shown in the top row. Where post-processing is needed, new data are not integrated with other data until later. New and existing data can be summarized and displayed together.

teams, and perform queries on large existing volumes of data.

The improved level of detail provided by mapping and attributing using a mobile GIS makes archaeological survey more theoretically rigorous as well. Archaeological “sites” on the Earth’s surface are often spatially complex distributions with artifacts from a variety of occupation periods intermingled on the surface. Archaeologists sometimes argue that expediently recording the distributions as merely “sites” with a hasty sketch map (Figure 3a) is justified due to the poor temporal control offered by surface sites, and because surface sites

are often disturbed. Subsurface archaeological excavations into stratified deposits, on the other hand, are painstakingly slow but they can give archaeologists detailed information about change over time. Archaeological sites on the surface are the complement to excavation because the sites are easier to locate and document, and therefore the strength of archaeological survey data is in statistical generalizations that derive from large, but often expedient, survey projects.

Because surface sites are spatially and temporally complex, it would be preferable to document the archaeological features at a finer level of detail

Figure 2. Example of a survey following a river terrace with parallel transects at a 15-meter interval. In this survey only one mobile GIS unit is used. GPS units carried by the surveyors at either end of the survey line mapped the extent of all surveyed areas.

than merely designating the “site” and its boundary. If the unit of analysis for surface distributions was each individual locus of artifacts that together form an archaeological site or, better yet, the individual artifacts themselves, then the GIS data would be more closely documenting the ancient activities of the people who created the sites (Dunnell and Dancey 1983; Ebert 1992, but see Binford 1992). For complex, well preserved surface sites that warrant careful recording, mobile GIS is a suitable technology for rapidly delimiting artifact concentrations on Earth’s surface at a scale that is significantly finer than the general site-level recording commonplace in past surveys. Yet, as

time is always short when doing survey fieldwork, any technological improvement to archaeological recording methods must be time efficient and have the option to be very expedient or more detailed as needed. There are limitations to what can be learned from surface sites because they are frequently disturbed and often have temporally and spatially mixed archaeological features, so above all survey recording involves balancing time commitments while recording sites.

There are analytical limitations to surface archaeological distributions that justify a certain degree of expediency when recording sites that are less relevant to the thrust of the research. A com-

mon resolution to time-constrained data recording is to gather the minimum valid sample; however, time does not even permit sampling at every archaeological site. The custom mobile GIS configuration described here permits archaeologists to record the spatial structure of surface sites using a variety of geometry types and to generalize about the variability within the distributions as needed. There are statistical weaknesses to the method described, and *reliability* or repeatability is low, but the technique used is considerably more effective than the older method for site recording in a given period of time. The customizability of mobile GIS permits researchers to prioritize elements of data acquisition that are deemed important and to expedite data acquisition for less important features.

Mobile GIS Implementation in the Upper Colca Survey

The implementation issues faced by an archaeological survey project using mobile GIS are relevant to most scientific fieldwork and resource management projects seeking to record and manage field data digitally. It is important, above all, to begin preparing and testing the hardware and software in a simulated fieldwork environment well ahead of the anticipated fieldwork season to avoid the possible loss of valuable field data. For the Upper Colca Survey the preparation for fieldwork using mobile GIS involved three main steps: digital data preparation, equipment testing, and establishing reliable organization and software structure prior to beginning fieldwork.

As with many GIS projects, regional digital data first had to be assembled or created because there were no prepared GIS datasets available for the study area in rural Peru. These data were principally 15m imagery and 30m absolute DEM data from the ASTER sensor, and vector data derived from these raster sources. Derivative vector data of interest to the archaeological study, such as contours, hydrology, and environmental polygons, were created prior to the survey because, typically, vectors are smaller and faster to work with on a mobile GIS than raster layers. For example, archaeologists working in the Andes know that high-altitude marshland *bofedales* have long served as valuable resource patches in the arid *altiplano* environment. Using the NDVI vegetation index function (Lillesand and Keifer 1994), these marshlands were delimited from the ASTER imagery prior to fieldwork as polygons for use in locational modeling and for reference in Arcpad.

Additional reference layers, such as georeferenced scans of all paper map layers, turned out to be very useful for making visual connection between the small Arcpad screen and the government printed topographic field maps in surveyors' hands. Uploading scans of the paper maps into the mobile GIS is one way of somewhat reducing the divide between the mobile GIS user environment and the paper map environment of the rest of the team. The ability to reference paper maps scans inside the mobile GIS permits the GIS user to quickly describe or point to features on the same paper maps that the rest of the team is referring to, reducing the divide between the two media.

Georeferencing, Hardware, and GPS Tests

Tests of data georeferencing, GPS performance, and GPS post-processing should be conducted prior to beginning fieldwork. Georeferencing accuracy can be evaluated to ensure that existing data adequately register with new positions recorded by the GPS antenna. During preliminary trips, GPS performance, reception, and accuracy can be assessed and experimental vectors of various sizes mapped in order to determine the minimum feature size that can be recorded using polygon geometry. The Upper Colca survey used Trimble GPS equipment that was post-processed using correction files from the AREQ International GPS System base station located 100 km away (Kouba 2003). Trimble Pathfinder Office and GPSCorrect reported average horizontal accuracy of 1.2 m. Research crews should begin the fieldwork with this kind of information because it influences how data recording decisions are made throughout the season. Since GPS accuracy was found to be approximately 1.2 m, it was decided at the beginning of the Colca survey that it was not worth mapping features less than 3 m across as polygons, and that for such small polygons an individual point should be mapped instead.

When evaluating the robustness of the equipment one should make sure that cables and plugs are rugged enough to resist repeated flexing. The hardware used during fieldwork in the Colca area (see Figure 1) included a Trimble Pocket GPS connected to a Dell Axim Pocket PC through a "rugged" D9 serial-to-CompactFlash slot adapter; this turned out to be a relatively fragile connection for fieldwork. While camping out at high altitude the life of the instruments' batteries was a critical concern, and therefore batteries were conserved at every opportunity by turning off the Pocket PC

backlighting, leaving the equipment off when it was not in use, and by keeping batteries warm at night in sleeping bags.

Software and Form Design

Software issues such as data organization, custom attribution forms, and data backup procedures should be designed and tested prior to beginning fieldwork. The process of exporting data from the main GIS to the mobile system for editing, and then reintegrating the changed data from each mobile system back into the principal GIS database, is a potentially complex procedure analogous to “synching” a personal organizer. Projects using multiple mobile GIS units will want to familiarize themselves completely with this process prior to gathering real data because of the increased potential for overwriting or otherwise losing new data when numerous machines are involved.

Reference data, particularly raster layers, are generally cropped to the project area so that the file sizes are small enough for the mobile GIS unit. With the ESRI ArcGIS extension Arcpad Tools, specified geodatabase, shapefile, and raster data layers are cropped to the project area for exporting. Mobile GIS users will probably wish to manage their *reference data* in a separate directory from their *editing data*. Reference data such as the DEM layer, scanned maps, and environmental data are a relatively large static dataset that remain mostly unchanged throughout the field season. Edited data, on the other hand, are a smaller collection of vector files edited during daily fieldwork that ought to be backed up frequently. These data may be post-processed, and they are subject to a “check-in/check-out” procedure from the main database on a regular basis. Maintaining a separate folder of edited data makes it convenient to back up the work frequently. For example, during the Upper Colca Survey it was not practical to pack a laptop up to the high altitude camp at 4900 m. Backing up the new vector data was simply a matter of copying the 2 MB editing data directory to a CompactFlash card using the PocketPC file explorer.

Pre-fieldwork testing of data attribution forms is an important step, particularly if there is flexibility designed into the recording system. As with traditional paper-based forms, the digital form is intended to expedite the recording process, prompt researchers to record appropriate data, and generate comparable and consistent data for each record. Forms need to be tested to determine if data are being stored in the proper data formats and to make sure that any errors in the forms and

associated scripts are resolved while tech support services are still available.

Forms should be tested to see if the organization of the interface conforms to real-world fieldwork situations. Traditionally when archaeologists encounter a site, one member of the team usually gets the site forms started before the site has been evaluated. Most GIS data structures usually require that a “spatial container” for the record, such as a polygon, is created prior to attributing the record. The workflow is thus reversed because the geometry of the feature must be mapped before any attributes are assigned to the feature. There are software solutions to this issue; for instance, proxy attribute forms could be filled ahead of time and then assigned to geometry, but researchers might be well advised to adjust their data acquisition routine to a geometry-oriented workflow.

The logical organization of the interface can be tested through simulated data acquisition prior to fieldwork. The limited screen size of most mobile GIS devices requires that attribution forms are organized onto small pages, but these pages can be structured to match the data acquisition stream of the field measurements.

In designing for archaeological research it was determined that pull-down menus (ComboBoxes) are the most space-efficient interface controls; they minimized the need for typing so they were used extensively (Figure 4). Interface designs involve making a compromise between research needs, the intuitive user interface, and the technical limitations of mobile GIS equipment. A principal challenge in preparing digital forms for archaeology was in making them general enough to accommodate wide variability in phenomena, yet narrow enough to be attributed quickly, using meaningful data categories. Thorough testing of the data workflow is critical at this early phase so that valuable research time is not wasted.

Site, Locus and Point Features Recording with mobile GIS

The Upper Colca Survey used a spatial provenience system expressly designed to make the most of mobile GIS record keeping; the team prioritized mapping artifact concentrations as loci within archaeological sites and then tracked the loci with their artifacts through unique ID numbers (see numbering in Figures 3b and 5a).

An example of the recording method used is presented below. While walking parallel transects (see Figure 2), the team of surveyors completed the following steps:

Figure 3. Maps for hypothetical sites recorded in less than one hour. (a) A conventional sketch map showing only general site features and site sectors in their approximate positions. (b) Mobile GIS site map with 1-2m dGPS error. Internal distributions, such as the fried-egg density gradient model shown here, can be assessed and rapidly mapped.

1. *Finding a possible site.* A surveyor calls out that he/she has encountered a probable archaeological site and the GPS units recording either end of the survey transect are stopped. Isolated artifacts are sometimes recorded outside of sites, but due to time constraints isolated artifacts were only recorded when they were unusually interesting. Because loci were more narrowly defined than sites, all loci fell inside the sites.
2. *Establishing the site boundary.* The team assembles and begins to delimit the boundaries of the site with wire-pin flags while taking into account the distribution of artifacts and features. During site recording a spatially inclusive boundary is delimited as a polygon using mobile GIS. The site is always given the first ID number for the cluster. Figure 5b presents descriptions of what these geometry types are. Let us assume our hypothetical site is polygon ID #112.
3. *Evaluation of loci.* Concentrations of artifacts and structural features within the site are evaluated using previously defined criteria in order to determine if they qualify for a locus. Loci are recorded separately and in greater detail.
4. *Documenting points.* Temporally diagnostic artifacts are mapped by using point geometry and

Figure 4. Example of a lithic locus form in Arcpad. In the background, two sites and contour lines are overlaid on an ASTER scene.

5a. Example of ID# System

110 - Site-a "Mayemeja"
A sketch map showing walls, a ceramic scatter, distinctive artifacts and stream.

111 - Lithic-p, Isolated Projectile Point

112 - Site-a "Pokomoko"

113 - Lithic-a, Low den locus in 112

114 - Lithic-a, Med density locus in 112

115 - Lithic-a, High density locus in 112

116 - Sample-p, Highest Dens in 115

117 - Sample-p, Random in 115

118 - Sample-p, Random in 115

119 - Ceramic-p, Diagnostic sherd in 112

120 - Ceramic-a, Low dens locus in 112

121 - Structure-a, Locus in 112

122 - Structure-p, Reference in 120

123 - Structure-l, Walls in 120

5b. Shapefiles and forms appropriate to data type

Class	Geom	Point Position	Line / Polyline	Polygon / Area
Sites <i>Site-level features</i>		Site-p, Sample-p <i>Site datum, mapping stations, 1x1m collections.</i>	~	Site-a <i>Site boundaries.</i>
Lithics <i>Stone artifacts</i>		Lithic-p <i>Diagnostic projectile point locations.</i>	~	Lithic-a <i>Lithic locus boundaries.</i>
Ceramics <i>Pottery</i>		Ceramic-p <i>Diagnostic ceramic locations.</i>	~	Ceramic-a <i>Ceramic locus boundaries.</i>
Structures <i>Architecture or natural shelters</i>		Structure-p <i>Diagnostic structural features, structure map sub-data.</i>	Structure-l <i>Terraces, walls, rockshelter entrances, rock art panels.</i>	Structure-a <i>Enclosures, structures.</i>

Figure 5. (a) An example of a part of an ID # system that prioritizes spatial provenience by connecting GIS geometry with other data such as collections and photos by incrementing a single ID # series. (b) Archaeological Shapefile names and descriptions. Each of the Shapefiles had a form associated with it that prompted the user with fields appropriate to that data type.

collected into a bag labeled with the unique ID number corresponding to a given GIS record. In Figure 5a these points include points #111 and #119.

5. *Mapping of loci.* The mobile GIS user visits each locus with the archaeologist who had reviewed it to facilitate documentation. The locus is mapped with a polygon and attributed based on the evaluation of the archaeologist. Photographs and other data are gathered and linked to the GIS data through unique ID numbers. Loci in Figure 5a include polygons #113, 114, 115, 120, and 121.
6. *Sampling from selected loci.* Of particular interest to this research were possible obsidian production workshops, features described as "High-density lithic loci." or these features a hasty estimate of surface artifacts was inadequate, and so a 1x1m collection unit sampling strategy was developed that will be described in more detail below. In Figure 5a these sample points correspond to points #116-118.

Attribute Forms

Aside from the site datum points and site boundary polygons, three dominant feature types characterized the archaeological data set in the mobile GIS. Each archaeological data type had an attribute form associated with it that recorded information appropriate for a given feature.

Page one of the digital forms comprised a unique ID number generated from a script and a range of numbers for digital photos (JPEG files)

documenting a feature. The second page (shown in Figure 4) contained specific information about the feature type, such as Site, Locus, or Point information. The third page contained eight pull-down menus with environmental attributes for geology, exposure, and other local variables. These values were usually the same within a given site so the values were "sticky;" they were stored in temporary memory between recording events, and the editable form was repopulated automatically unless a new site feature was being recorded. The final page contained a "Comments" field that accepted up to 255 characters and included a button that would open Pocket Word with a text file named for the unique ID #, for taking additional notes if necessary. A link to a separate application that permitted MP3 compression of voice-based comments was available as well, but because the processor demands of sound encoding overly hampered the functionality of the Pocket PC for the GIS application, the feature went unused.

Variability within a Locus

A basic complexity of archaeological survey is that artifact concentrations frequently contain a variety of artifact types, perhaps dating to completely different occupations. This variability presents a particular challenge for a fast mobile GIS based recording system because in lieu of sampling, all the archaeologist has time to do is to document his or her rapid assessment of the artifacts that are found within individual loci geometry mapped into the GIS. Additionally, despite of the variabil-

ity present within the locus, the archaeologist must generate data over the course of the field season that are consistent and comparable.

During the Upper Colca Survey this difficulty was addressed by documenting a primary and secondary “component type” that best characterizes the locus using the custom interface developed for the project. The problem: *How does one evaluate and map a scatter of, say, 5,000 stone flakes in less than one hour, as well as estimate the percentage of obsidian to another material type, such as chert?*

In order to achieve statistical rigor and reliability, a sampling strategy was needed. Sampling and collecting artifacts is time consuming, and sampling at every concentration of lithics near a quarry is also unrealistic because there are so many lithic artifacts in such areas. Sampling was therefore carried out at “High Density Loci” with artifact concentrations deemed most worthwhile given our research goals, while a less rigorous approach was applied for artifact distributions of lesser importance. A solution was devised appropriate only for cursory inventory.

This solution captured variability by estimating the proportions of the two dominant groups within a given polygon. At a site with a low-density lithic locus (see Figure 3b), the concentration of stone artifacts was mostly obsidian material but also included artifacts made from chert, chalcedony, and quartzite. The mobile GIS user walked around the locus with the GPS running, and the area was recorded into the “Lithics-a” ShapeFile (Figure 5a). Lithic concentrations of medium and high density were found inside the locus, creating a ‘fried-egg’ density map. Subsequent to delineating the locus with a GPS, the custom form (Figure 4) appears. Several steps are followed in filling out the form.

- The primary “axis” of variability is determined. In this case, it was stone material type.
- Using this variable, the largest group is characterized. This spatial Component 1 was described as “Material: Obsidian,” and other attributes of interest to lithic analysis such as amount of cortex, size of debitage, and artifact density in the component, were rapidly estimated. In our case, the density was “Low.”
- The second most represented group, spatial Component 2, is characterized and its attributes are evaluated, again as quickly as possible. Any subsequent groups were disregarded for expediency and because of the error in estimation and low reliability of the method.
- The proportion of stone artifacts in the polygon estimated to meet the description of Component 1 is entered in the field labeled

“C1% of Locus,” and an estimate is also generated for Component 2.

The method worked for a rapid inventory, and a general estimation of materials, and their characteristics and densities within loci was produced. Archaeologists were encouraged to describe the variability between Components 1 and 2 in terms of only one variable at a time. For example, if there were notable differences in both Material Type and Debitage Size in a particular locus, then a second polygon was created. Alternatively, the first polygon was copied, and the different “axes” of variability were distinguished independently. An instant typology was generated for each polygon by emphasizing the greatest variability within the locus, yet, this was considerably more spatially explicit than rapid archaeological survey had been in the past despite small investment in time. Since time efficiency was a major objective of the Colca Survey with recording all but the very highest density lithic concentrations, the fact that modern digital equipment such as the mobile GIS used in this archaeological survey can be modified and streamlined by the archaeologists to suit the needs of research without recourse to a professional programmers opens up a lot of possibilities.

Sampling High-density Loci

For the purposes of the Upper Colca project *High-density loci* were defined as areas where the density of the artifact scatter appeared to exceed 10 artifacts per m². As with all loci, these concentrations were mapped using the mobile GIS interface, but then High-density loci were further characterized by collecting all artifacts within two or more 1x1 m sample squares for later analysis back in the lab. The Arcpad SampleDesign script was used to pseudo-randomly place, using an unaligned-grid method, a sufficient number of square sample units to cover at least 0.01 of the Shape Area (m²) for the locus as reported in Arcpad. This works out to a 1 m² collection area for every 100 m² of polygon area. The GPS indicator was used to navigate to those points. When documenting each sample an overhead photo was taken of the 1x1m area from near-nadir for later georeferencing, and then artifacts were completely collected. One or more units were randomly placed somewhere within the polygon, and one unit was always placed right on the location of estimated highest density. During the Colca Survey such collections resulted in an average sampling fraction of 0.014 among the twenty-two samples that were collected during the

course of the field season in this process of sampling high density loci.

Collection

Traditionally, it has been impractical for archaeologists to retain precise spatial provenance for surface artifacts that are not particularly interesting or rare. Collected artifacts are aggregated by site, sector, or by a locus. However, artifact collection is increasingly seen as a destructive practice because the archaeological site is diminished when portions of the surface materials are removed. Archaeologists have an obligation to use the best spatial technology available to record artifact distributions as they collect them because, as with excavation, once archaeologists have removed artifacts from their context, even systematically, the site is forever compromised.

The collection strategy used in the Upper Colca Survey consisted of assigning a unique ID number from a single number series to all spatial proveniences, point locations, loci, or entire sites—very much like postal zip codes for street addresses. After four months of fieldwork, 1100 spatial provenance numbers had been assigned from the series. The unique ID# connects field collections with space through GIS records and with records in a Microsoft Access database used during artifact analysis in the laboratory, where individual artifacts were given a second range of non-spatial lab ID numbers after a decimal point. Ultimately, a single ID# such as “120.3” connects artifact number 3 (a lab ID#) that was collected from the area mapped as 120 (a ceramic locus) to the digital database for statistical analysis and through to the artifact collection inventory in museum storage archives. This system requires that archaeologists write a lot of tags for artifact collection bags. An interesting alternative to handwriting the unique ID# on labels for sample bags collected in the field is to bring a sheet of pre-printed barcode stickers. As the sticker is placed on the sample container, a serial barcode scanning wand can scan the barcode value directly into the GIS record. The barcode scanner approach is somewhat restrictive, however, because the mobile GIS unit must be available to scan every collection bag.

Other Data Types

As a systematic pedestrian survey of extensive areas, archaeological survey work presents an opportunity to collect other data as well. During

survey work in the Colca area, a separate set of GIS data was collected that consisted of non-archaeological data. These included geological sources of stone material such as chert outcrops and natural obsidian flows. Similarly, fresh-water springs and other resources of use to past peoples were mapped in. Mountain summits, trails that may follow pre-Hispanic trade routes, and other such environmental features were also mapped. Thousands of digital photos were taken, including a number of stitched panorama photos. The location of these photos was mapped with the mobile GIS using a form to enter the JPEG file numbers, as well as the cardinal direction and an estimate of distance for photographs of distant objects. The variety of data types that were determined to be worth recording during this survey project underscores the need for individual flexibility in interface design for mobile GIS.

Implications of Mobile GIS for Fieldwork

With the prevalence of GIS in laboratory analysis, the growing use of mobile GIS for scientific field research seems inevitable, although the applicability of mobile GIS to specific applications depends largely on the extent to which mobile GIS meets research needs. Minor benefits of mobile GIS, such as a time and date stamp associated with every measurement, augment the data that are being gathered in unobtrusive ways. A more elaborate system might gather extensive metadata concerning research methods and data structure into an automatically generated digital log file.

Statistical summaries and visualization applications, although not yet available in mobile GIS platforms, would have proved useful during the Upper Colca Survey. The ability to estimate spatial variation measured on archaeological variables would have been useful in selecting the sampling strategies and for placing test excavation units (Hodder and Orton 1976; Redman 1987). Were researchers able to investigate new spatial data in conjunction with existing datasets using the exploratory data analysis approach (Tukey 1977) — while they are in the field it would open up new research strategies combining information from and existing digital datasets. Statistical indices, such as the degree of spatial autocorrelation among particular classes of data, would be useful to know in the field. Geostatistical methods such as kriging, familiar to archaeologists in lab analysis (Lloyd and Atkinson 2004), may have application in fieldwork contexts

as well should those tools be available in mobile GIS systems.

Low-impact Management Applications

One of the most promising aspects of mobile GIS as a reference system is in cultural resource management applications. The ability to transport complex datasets into the field means that resource managers have access to a variety of specialized field data that may otherwise exceed their knowledge. Transporting complex datasets the other direction – from the field site back to the lab is also made possible, such that analysis can increasingly take place in the field and artifacts can remain in their original spatial context. Collecting and removing certain archaeological materials effectively destroys the site for future visitors and for researchers who may wish to re-evaluate the site. Additionally, the budgetary expense of curating artifacts makes in-field analysis an attractive alternative to systematic collection, particularly for isolated sites that are unlikely to be disturbed. As the legislative requirements surrounding research in archaeology are becoming more and more restricted in many parts of the world, some kind of a computerized record-keeping system for in-field analyses is almost mandatory.

In Australia, a “Permit to Destroy” must be acquired before artifacts can be recovered from the surface, leading many archaeologists to conduct rapid artifact analysis in the field using portable equipment. During in-field analysis, a stone-tool expert might record over 30 attributes from a lithic artifact during a two-minute pause in the survey, and then drop the artifact in its original context. Similarly, archaeological resource management in some units of the U.S. National Park Service has moved away from collection as a management strategy (see McVickar 2001; Powers and Zandt 1999). If these examples of non-destructive survey procedures in archaeology are an indication of where resource management is going, there is a growing need for accurate geographical control in management applications.

Future Directions

As mobile GIS hardware becomes smaller and more widely available, research and management applications will certainly multiply. Data collection with digital instruments that communicate through local wireless such as Bluetooth will facili-

tate integrating data from various instruments into a single spatial database through mobile GIS (Figure 1, Possible Improvements). For example, a digital calipers and scale with built-in wireless could be used to expedite taking measurements from artifacts in the field with a direct input to mobile GIS forms, and further reduce the need for artifact collection. Similarly, Total Station data could be integrated wirelessly into the mobile GIS. Archaeologists do not commonly use multimedia such as digital video, but cultural anthropologists, for example, might shoot ethnographic footage and a DV camera could transmit the filename to a mobile GIS form for reference in the spatial database documenting the video location.

At a different scale, wireless networking over great distance using cellular or satellite networks is becoming a reality. Research applications of mobile GIS will benefit significantly from such interconnectivity, with the ability to access large, remotely stored datasets on demand and to acquire newly updated information from other research teams in real time. In a multidisciplinary research project, individual investigators would be able to consult across the network with experts from other disciplines and conduct a kind of guided fieldwork. For example, a variety of ceramics types were found by the archaeological survey in the Colca area. A digital image of an unknown ceramic type could be transmitted electronically to other archaeologists who might be able to rapidly identify the ceramic style and reply via email to the mobile research team.

Wearable computers also hold promise for mobile GIS applications in field research. Juggling a Pocket PC, a GPS unit, and a digital camera in one's hands on archaeological survey is wearisome. Having to care for so many devices in the field makes it more difficult to do basic archaeological work, such as inspecting artifacts. A wearable computer would free one's hands for inspecting artifacts and for walking or scrambling in difficult terrain. It would also expedite feature recording because isolated artifacts could be documented quickly without disrupting the survey line.

Mobile GIS thus promises to influence significantly the practices of scientists working in field sites in the near future. Some of these impacts are as follows.

- *Field contributions*—researchers in the field will have more influence on data production as spatial analysis tools become available away from the workstation in the research lab.
- *Field-to-laboratory connection*—the digital link between sampling activities in the field and

the lab analysis will become more integrated through the use of a mobile GIS, enhancing both sides of the research process.

- *Scale*—the distinction in scale between local and regional datasets will become more blurred as researchers carry and work with ever larger datasets in the field. However, this also brings up a host of issues regarding scale, data quality, and the appropriate use of data.
- *Rapid data dissemination*—spatial data is continuously being integrated and managed, simplifying the production of regular update reports and encouraging faster data publication schedules.

Potential problems

Carl O. Sauer noted in 1956 that: “There is at present enthusiasm for field mapping and their techniques... But map what and to what purpose? Is not this possibly another horn of the dilemma?...Routine may bring the euphoria of daily accomplishment as filling in blank areas; the more energy goes into recording, the less is left for the interplay of observation and reflection.” A realistic vision of future implementations of mobile GIS is not without drawbacks, particularly regarding data accumulation, technical complexity in field equipment design, and future restrictions on access to data.

A major concern with added computer complexity and the potential for greater raw data accumulation is that the theoretical goals of the research can be overlooked in the deluge of data that are made possible with mobile GIS. As cartography shows, the appropriate use of scale can demonstrate patterns in data that are obscured when detail is emphasized above all else. The focus on data accumulation and on technically complex research equipment can lead to field researchers becoming computer experts at the expense of more traditional subject matter expertise.

In contrast to the existing paradigm of field equipment, where a quiver of reliable instruments is brought into the field so that each does one job and does it well, mobile GIS is an integrative system that transports the complexity of modern computing to isolated field locations. Instead of a simple mercury thermometer, a tape measure, and a log book, for example, scientists are bringing miniature computer labs into the field and will potentially have to tackle scripting and networking problems with limited access to technical support services. There is no reason that a rugged system cannot be thoroughly tested before fieldwork be-

gins. However, flexible interface designs are needed for applications such as archaeology, and with greater flexibility comes reduced predictability in the circumstances in which data will be acquired. It is possible to write strong error-handling into the software, but if field equipment is being used in unexpected ways there is an inherently greater potential for unforeseen problems in field recording that can compromise the research. In sum, flexibility may come at the expense of dependability. An independent backup system could be designed into mobile GIS data acquisition strategies because field data are usually expensive and difficult to acquire.

Despite the analytical and organizational advantages of digital record-keeping and map display, it would be difficult to argue that orienteering and data acquisition into a tiny Pocket PC was as intuitive or pleasurable as using a map. The small screen, the inability to read the screen with sunglasses on, the fragility of the system, and above all the concern for GPS battery life, made working with the Pocket PC in the Colca more of an experiment than a viable replacement for paper. Given the rapid pace of development of computer interface technology, however, these obstacles to greater integration of mobile GIS into field seem like the least significant issues over the long term.

The use of a mobile GIS survey planning and recording system in the Upper Colca Survey also had detrimental effects on survey team cohesiveness. There was a notable knowledge gap between the person who held the mobile GIS unit and the rest of the team. As research progressed throughout the season, this gap increased because all the new data were logged into the mobile GIS, but it was impractical to print out detail maps showing data distributions for the team members without access to the computer. Unlike paper documents and map sheets, which can be consulted and pointed at in a group as the daily strategy is determined, most mobile GIS systems use a relatively private interface that fosters instead a top-down relationship within the team. As mentioned, scanning the paper maps into the mobile GIS can ease the communication gap between the two systems but, ultimately, every surveyor without a mobile GIS unit is at a disadvantage.

Conclusion

Mobile GIS has tremendous potential and will probably define the way field research is done in the 21st century, but it presents new hurdles that are foreign even to expert GIS users who

are familiar with solving problems in a laboratory. Many problems that plagued early adopters of the technology have been solved: rugged mobile GIS hardware is widely available, solar and other energy cell development is advancing, and CD burners and Flash RAM largely solve data backup problems.

Recent archaeological survey work using mobile GIS showed that a great deal of pre-fieldwork preparation is required in order to have a reliable data recording system. Site documentation strategies can make the most of the rapid mapping capability of GPS by estimating the characteristics of artifacts within polygons, and by sampling and collecting from the more important features for later analysis. Mobile GIS will contribute to a more thorough and theoretically responsive methodology on the part of archaeologists because the task of maintaining spatial relationships, formerly a laborious part of archaeology, is managed by the software. Data exploration, both in the field on mobile units, and back at the laboratory using mobile GIS acquired data, is much improved.

Many of the limitations of mobile GIS encountered on fieldwork are a consequence of the novelty of the technology, and undeveloped potential for the various instruments and cameras to interact wirelessly. The principal challenges for those bringing mobile GIS to their field research settings will revolve around the issues of flexible data acquisition, reliable designs, and retaining a focus on the larger research issues despite the many technical details under consideration.

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