Unlocking the spatial dimension: digital technologies and the future of geoscience fieldwork

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Abstract: The development of affordable digital technologies that allow the collection and analysis of georeferenced field data represents one of the most significant changes in field-based geoscientific study since the invention of the geological map. Digital methods make it easier to re-use pre-existing data (e.g. previous field data, geophysical survey, satellite images) during renewed phases of fieldwork. Increased spatial accuracy from satellite and laser positioning systems provides access to geostatistical and geospatial analyses that can inform hypothesis testing during fieldwork. High-resolution geomatic surveys, including laser scanning methods, allow 3D photorealistic outcrop images to be captured and interpreted using novel visualization and analysis methods. In addition, better data management on projects is possible using geospatially referenced databases that match agreed international data standards. Collectively, the new techniques allow 3D models of geological architectures to be constructed directly from field data in ways that are more robust compared with the abstract models constructed traditionally by geoscientists. This development will permit explicit information on uncertainty to be carried forward from field data to the final product. Current work is focused upon the development and implementation of a more streamlined digital workflow from the initial data acquisition stage to the final project output.

Keywords: geospatial data, field studies, digital cartography, surveys, three-dimensional models.

Geoscientists understand that their subject is inherently both spatial and temporal in nature. Although advances in geochronological and chronostratigraphical methods have improved our temporal resolution markedly in recent years, spatial resolution, particularly for field-based observations, has not improved significantly during the last two centuries. With the recent convergence of key digital technologies for the collection and analysis of spatial data, we are now on the threshold of significant improvements in spatial resolution in general geoscience fieldwork. Specifically, digital fieldwork methods that have previously been available only to industry and national survey personnel are now within the price range of most geoscientists.

Since the mid-18th century geospatial data have generally been presented on geological maps (Greenly & Williams 1930), and are a fundamental tool that shows the distribution of rocks on the surface of the Earth and their 3D arrangement underground (Maltman 1998). Geologists debated 150 years ago whether it was better to report observations in a narrative form or a graphical form using maps (Turner 2000). The modern-day ubiquity of the geological map was emphasized by Wallace in a 1975 Jacklin lecture (quoted by Barnes & Lisle 2004): ‘There is no substitute for a geological map and section—absolutely none. There never was and there never will be.’ In this paper we pose the question whether the acquisition, visualization and analysis of high-resolution digital geospatial field databases will similarly revolutionize the Earth Sciences by adding an unparalleled degree of spatial precision to geoscientific observations.

Paper-based fieldwork methods have made fundamental contributions to our current state of knowledge of the Earth’s surface and subsurface geology. However, they have remained virtually unchanged and are essentially the same as those used 200 years ago. In the geosciences, as in all scientific disciplines, digital methods are increasingly used for data management, analysis and visualization, but for fieldwork these activities generally take place back in the laboratory and are rarely used routinely in the field. Most geoscientists already digitize their field data by transcribing into spreadsheets or databases, and by reproducing field maps on cartographic or graphic packages in the office or laboratory. More generally, there are continuing national survey initiatives to ‘digitize’ existing paper maps at a range of scales. We view this type of digitizing as a secondary process and contrast it with primary digital field data acquisition that is the focus of this paper. We suggest that the latter offers clear advantages to traditional methods.

A number of technological advances have increasingly helped to make methods of digital field data acquisition a practical, low-cost alternative to paper-based fieldwork systems (Fig. 1). In addition, these methods offer new types of spatial analysis that were previously impossible or impractical to achieve by conventional mapping methods. The cheaper components include handheld GPS (global positioning systems); lightweight palmtop or handheld computers capable of running mobile GIS (geographic information system) software with wireless communication. More expensive alternatives offer more functionality and spatial precision and include: more accurate differential GPS (DGPS) and survey-grade GPS receivers; laser ranging and scanning devices; and lightweight, energy efficient 2D (and increasingly, 3D) mobile display technology. A parallel development has been the increased availability of digital map and topographic data from national and international survey organi-
Pioneers have claimed that digital methods can improve the quality and efficiency of field data collection because they:
(1) have potentially better spatial accuracy than traditional methods; (2) streamline the workflow from ‘data acquisition to published product’; (3) allow better visualization of data in two dimensions and three dimensions; (4) yield further geological insights because of the enhanced ability to perform geospatial analysis in addition to more traditional geometrical or temporal analysis of geological architectures.

The aim of this paper is to explore the new digital fieldwork methods and examine their potential to improve our understanding of geological architectures. Where possible we use quantitative data to examine critically the benefits of digital v. traditional methods, and where quantitative information is lacking we provide a qualitative assessment on the advantages and disadvantages of digital methods compared with conventional approaches. Finally we discuss the current and future development of digital methods for geoscience fieldwork.

Geoscientific fieldwork

Geoscientific fieldwork is undertaken using a large variety of methods over a range of scales, and includes geochemical sampling, collecting geophysical data, reconnaissance mapping using remote sensing or highly detailed ‘cairn’ mapping (Table 1). Traditional fieldwork methods are well covered elsewhere (Greenly & Williams 1930; Barnes 1981; Compton 1985; Barnes & Lisle 2004). We describe here digital data acquisition systems that can be used for a range of geoscience fieldwork purposes. For some activities, such as geological mapping, it is desirable to interpret observations during the mapping process and to modify the interpretation as more information is acquired.

Fig. 1. A typical workflow for digital fieldwork. For mapping applications, outcrop data (attributes images, topography, etc.) are geospatially referenced using GPS and laser units (see text) and collected via a handheld computer. High-resolution survey methods are used to acquire centimetre-scale coverage of outcrops. At base the data are uploaded to desk- or lap-top computers and a variety of visualization and analysis outputs are produced. GPS, global positioning system; PDA, personal digital assistant; RTK, real-time kinematic.
Digital geological fieldwork

In contrast to using paper-based fieldwork methods, the geoscientist collects GPS-located field data in a digital format on a handheld computer or tablet PC. The technologies have been adapted from mapping and surveying techniques that are now widely used in construction, engineering and environmental industries. The advent of portable and handheld computers allowed early pioneers to replace the field slip and notebook with a digital version (Struik 1997; Brodaric 1997; Briner et al. 1999; Bryant et al. 2000; Pundt & Brinkkotter-Runde 2000; Xu et al. 2000; Maerten et al. 2001). It was soon realized that by connecting a GPS receiver, automatic spatial referencing would be provided (Pundt & Brinkkotter-Runde 2000). A cheap, flexible system that is suitable for most general geological field data acquisition comprises three key components: (1) a handheld computer (PDA (personal digital assistant)) or other digital data-logger; (2) a GPS or DGPS receiver; (3) mobile GIS software (Edmondo 2002; Wilson et al. 2005) (Table 2). The key advantage of digital mapping over conventional paper-based mapping lies in the automatic recording of positional data for each observation, meaning that the geospatial context is maintained. Additional benefits include: the ease with which data are recorded in formats that are compatible with existing databases; the opportunity to map at varying scales (which can be changed 'on the fly' whilst mapping); and the ability to map onto different base layers, such as a remote sensed image, aerial photograph or topographic data layers (Fig. 2).

Most handheld GPS receivers designed for the leisure industry provide locational information to 3–10 m precision (Table 2) and are adequate for mapping at scales of 1:10 000 or smaller. DGPS receivers use additional data from geostationary satellites or land-based beacon stations to reduce systematic errors (e.g. as a result of atmospheric conditions) and provide spatial precision to 0.3 m, which is adequate for mapping at scales up to 1:300. An example of a simple digital mapping project carried out to provide a teaching resource is shown in Figure 2. The Assynt region, NW Scotland, is a world-famous site to view the Moine Thrust Zone and its foreland geology of metamorphic Lewisian basement overlain by red-bed deposits of the Torridonian and the Cambro-Orдовician shelf sequence (Johnson & Parsons 1979). Digital geological mapping to a precision of 0.3 m was carried out over a small part of this region. Contacts were mapped as

<table>
<thead>
<tr>
<th>Hardware</th>
<th>Typical claimed accuracy</th>
<th>Speed</th>
<th>Use</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handheld GPS, computer and mobile GIS</td>
<td>c. 3–10</td>
<td>Instant locational fix</td>
<td>Reconnaissance and regional mapping</td>
<td>£500</td>
</tr>
<tr>
<td>DGPS and mobile GIS</td>
<td>c. 0.3 m</td>
<td>Instant fix</td>
<td>Detailed mapping and attribute collection</td>
<td>&gt;£2000</td>
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<tr>
<td>Real-time kinematic (RTK) GPS units</td>
<td>Better than 10 mm</td>
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<td>6 mm at 200 m range</td>
<td>Automatic point collection up to 12 000 points per second; colour intensity mapping from digital cameras</td>
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<td>Aerial and ground-based photogrammetric methods</td>
<td>Variable depending on distance</td>
<td>Fast acquisition (minutes), slow set-up and processing (days)</td>
<td>Acquiring detailed images of beach-section and other flat-lying exposures</td>
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</tr>
</tbody>
</table>

Table 1. An illustration of the ranges of geological fieldwork and digital equivalents

<table>
<thead>
<tr>
<th>Mapping type</th>
<th>Reconnaissance</th>
<th>Regional</th>
<th>Standard1</th>
<th>Detailed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical map scale</td>
<td>1:250 000 or smaller</td>
<td>1:100 000–1:50 000</td>
<td>1:10 000–1:25 000</td>
<td>1:10 000 or larger</td>
</tr>
<tr>
<td>Traditional methods</td>
<td>Remote sensing, photogeology, ‘blind’ spot sampling (e.g. using helicopter)</td>
<td>Appropriate scale base maps or aerial photographs, or simplified 1:10 000 field slips</td>
<td>1:10 000 field slips</td>
<td>Planetabling</td>
</tr>
<tr>
<td>Geospatial abstraction</td>
<td>Very high implicit in sampling strategy prior to fieldwork</td>
<td>High in field and also during cartography</td>
<td>Medium levels of abstraction in the field; captures some outcrop structure</td>
<td>Very little abstraction; can capture the entire outcrop</td>
</tr>
<tr>
<td>Typical wavelength (of structures)</td>
<td>&gt;10^2 m</td>
<td>10^2–10^3 m</td>
<td>10^2–10^4 m</td>
<td>10^-2–10^4 m</td>
</tr>
<tr>
<td>Digital equivalents</td>
<td>Remote sensing, aerial photography</td>
<td>Digital elevation models, digitized maps and GPS-referenced data collection</td>
<td>Digital elevation models and GPS or DGPS-referenced data collection</td>
<td>Real-time kinematic GPS, laser scan, etc. (see text for details)</td>
</tr>
</tbody>
</table>

1This refers to normal UK practice, which corresponds to BGS standard surveying and university undergraduate projects.

(Jones et al. 2004). By incorporating visualization and analysis into the mapping workflow, digital methods can aid the interpretation process and examples are given at the end of this section.

Table 2. Hardware used for digital mapping and survey, typical speeds, use and cost

1Aerial and ground-based photogrammetric methods were used to acquire high-resolution images of outcrops and outcrop structures. These images were used to produce detailed geological maps of the region, which were then used to create a digital elevation model (DEM) of the outcrop.

2The key advantage of digital mapping over conventional paper-based mapping lies in the automatic recording of positional data for each observation, meaning that the geospatial context is maintained. Additional benefits include: the ease with which data are recorded in formats that are compatible with existing databases; the opportunity to map at varying scales (which can be changed ‘on the fly’ whilst mapping); and the ability to map onto different base layers, such as a remote sensed image, aerial photograph or topographic data layers (Fig. 2).

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New high-resolution digital survey methods

Fine-scale (centimetre) digital acquisition is now possible using a variety of geomatic surveying equipment (Table 2) with either automatic attribute (e.g. colour intensity) or user-enabled attribute (e.g. surface slope, bedding dip) recorded along with the positional data. Recorded data may be ported to high-performance visualization systems and viewed at scales up to and larger than 1:1. Although largely developed for engineering use, these methods are now being adapted for geoscience data (Xu et al. 2000; Bellian et al. 2002; Ahlgren & Holmlund 2003; Rowlands et al. 2003; Jones et al. 2004; Pringle et al. 2004; Clegg et al. 2005). Laser scanning or reflectorless surveying methods (Fig. 1) are best used on steep, vertical or overhanging sections whereas aerial photogrammetric methods are more appropriate for beach or outcrop pavements. Kinematic or survey-grade GPS (Fig. 1) is used to geospacially reference individual surveys or can be used as a stand-alone acquisition tool.

The cluster of 3D data points generated during a survey is known as a ‘point cloud’ and may be meshed to form a 2.5D outcrop surface. Attributes such as bedding dip may be directly mapped onto this surface by using data collected at sample locations, or summarized on a contoured plot (Fig. 3a). Alternatively, the surface may be textured from digital photographs to form a 2.5D photo-realistic outcrop image displayed on a computer monitor (Fig. 3b–e).

Digital survey methods allow the user to carry out detailed interpretation in the laboratory on large 3D images. The user can map stratigraphical contacts, meso-scale tectonic and sedimentary structures, or weathering and other surface processes. The advantage over mapping on conventional outcrop photographs is the ability to constrain the true 3D spatial architecture of the outcrop. The ability to access parts of exposures that are inaccessible or require specialist-climbing apparatus is also a significant improvement. The user can easily continue the analysis at a later date to enhance the existing interpretation, add more detailed data, or supplement one dataset with other types of information. It is clearly desirable to add information that places constraints on the attribute of interest in the third dimension (i.e. into or out of the outcrop surface). This may be information from a borehole, a geophysical, or a statistical model of attribute values.

As an example we present results of a digital survey of 3D fault geometry. A very fine-scale network of minor faults were formed in Permian sandstones in the hanging wall to the Ninety Fathom Fault, a Late Palaeozoic to Mesozoic basin-bounding fault that is exposed at Cullercoats, NE England (Kimbell et al. 1989; Knott et al. 1996; Clegg et al. 2005; De Paola et al. 2005). The outcrops were captured using a high-resolution laser scanner and the points coloured from digital photographs taken from the same georeferenced position. The data were then loaded into an interactive visualization and fault surface fitting software package that allowed the 3D fault traces to be picked on the topographic surface (Trinks et al. 2005): 3D surfaces were fitted to the fault traces and the resulting fracture network was visualized and analysed (Fig. 4). The dataset is spatially referenced in global coordinates to 1 cm accuracy. The laser scan data took 3 h to acquire, including set-up time, followed by 2 days of laboratory analysis in which all discrete faults and fault arrays with spacing of 2 cm or greater were interpreted. To achieve this level of accuracy using traditional field surveying methods would be virtually impossible. A direct comparison between the virtual interpretation and the fault network geometries established by conventional structural analysis (De Paola et al. 2005) is in progress.

Field-based digital visualization

Geological information gathered by traditional geological mapping has generally been displayed in 2D representations such as geological maps, with cross-sections giving an interpretation of the subsurface geology. In the laboratory, increasingly powerful visualization packages combined with 3D screen technology can be used on workstations and desktop computers and now provide sophisticated immersive capabilities for data interpretation (Fig. 5). As discussed above, it is particularly useful to use 2.5D perspective views to study how geological formations and structures are related to topography. True 3D data volumetric data can be incorporated to build ‘solid’ geology models rather than a series of stacked surfaces or parallel cross-sections (Kessler & Mathers 2004), which may then be ‘exploded’ to examine details of the model.

To date, the 2D screens on handheld computers have generally been small, and the limited graphics capabilities of on-board mapping packages largely restrict data visualization to simple map-type displays in the field. Fortunately, graphics displays are now increasingly capable of displaying raster data at high resolution and this now allows an aerial photograph or digital elevation model to be used as a backdrop onto which new data are displayed. These displays can be used to view the equivalent of a traditional geological field-slip. However, they also allow...
more flexible methods of visualization that can be easily tailored to individual requirements. For example, on-screen data may be viewed at different scales in two dimensions using zoom and pan functions with different combinations of data layers displayed as required. The next stage will be to incorporate 3D viewer capability in handheld computers with software that will allow 2.5D models to be viewed in the field while the data are being collected, or for auto-stereoscopic screens to provide a genuine 3D perspective (Holliman 2005).

Field-based digital analysis methods

Digital geospatial referencing of all field data allows powerful spatial statistical and analytical methods to be applied to geoscientific problems (Berry 1987, 2000). Spatial statistics incorporate a variety of methods to describe how discrete or continuous data vary across a given area. These methods (e.g. point process, variograms and kriging) are particularly useful for data derived from digital fieldwork methods and allow the interpolation between sample points (Fig. 3a) and the calculation of standard error displays. Spatial analysis has developed from simple ‘geo-query’ searches on databases (e.g. ‘what is at location xyz?’), to methods involving map algebra, which perform mathematical functions on different map layers (Berry 1987). For example, Piazolo et al. (2004) integrated geological and geophysical datasets in a GIS to define the shapes and patterns of structural domains at a variety of scales in the northern Nagssugtoqidian orogen, west Greenland.

Many of these spatial statistical and analytical methods have yet to be developed for direct use in the field on a handheld computer, but can easily be performed on a lap-top at the field base. On-the-outcrop analysis methods such as rose diagrams, stereonet projections, frequency plots, dip analysis, structure contour estimation and intersecting plane calculations could

Fig. 3. Digital survey. (a) Results from a digital survey from Cullercoats (NE England). Attributes (in this case bedding dip in dolostones) are measured at stations that are precisely located (to sub-centimetre scale) by an RTK GPS. The display shows geostatistically interpolated bedding information and permits a fine-scale analysis of geological structure. (b)–(e) Results from a laser scan of cliffs composed of Permian sandstones at Cullercoats: (b) a point-cloud of x-, y-, z-coordinates; (c) the point cloud coloured with the intensity of the reflected laser signal; (d) the point cloud coloured from a georeferenced digital image; (e) a surface mesh fitted to the point cloud on which the digital image has been draped.

Fig. 4. Fitting 3D surfaces for (a) bedding and (b) faults from points picked on a laser scan dataset from Cullercoats.
relatively easily be programmed into handheld computers or provided as an ‘add-in’ to existing packages.

Assessing digital field data acquisition methods

Digital field data acquisition methods are evolving rapidly and here we discuss, and where possible test, the claimed improved data management, spatial accuracy, reproducibility of results, efficiency of workflow and understanding of 3D architecture that results from their use. We also assess the perceived disadvantages of digital acquisition methods, including poor integration and compatibility of software and hardware, bulkiness and ruggedness of field equipment, potential data loss and the effects on traditional mapping skills.

Improved data management capabilities

Geoscientists collect a wide range of different types of field data and record these on a variety of media when using traditional (non-digital) methods (Table 3). Digital geospatial databases allow many different types of geological data to be stored together, so that the user has a visual interface to all of the data collected for an area. Examples of data that may be included are field photographs, regional geophysical maps, aerial photography, satellite imagery, topographic data, previously digitized geological information, sample catalogues, geochronological data, geochemical data, etc. By comparison, such disparate types of data would traditionally be spread widely between field notebook, paper maps, isolated files on a computer, boxes of photographic slides or prints, library journals and loose papers. Digital data models are increasingly used to store geoscientific information and systems have been devised to handle combinations of numerical, descriptive and other non-numeric (e.g. image-based) data. A properly managed digital database offers considerably improved data retrieval, database searching, archiving and remote accessibility compared with conventional paper-based methods. Because most geoscientific data are spatial in nature (i.e. specific to a given location) it is not surprising that GIS are now widely used. GIS has evolved from its early use as a computer cartographic system and is now defined as ‘an information management system for organizing, visualizing and analysing spatially orientated data’ (Rhind 1992; Coburn & Yarus 2000, p.1; Longley et al. 2001). In its original guise, GIS largely dealt with 2D data that were mapped onto the Earth’s surface (Rhind 1992). However, it was recognized that to deal with volumetric spatial information or 3D geometries from subsurface data, a 3D GIS or a GSIS (geoscientific information system) was required (Mallet 1992; Turner 1992) and these have since been developed. GIS now combines digital database, spatial analysis and multi-dimensional mapping capabilities, which makes it a powerful analytical tool for the geoscientist.

Increasingly, Earth scientists solve new problems by analysing old data in light of new theories or knowledge (Rasmussen 1995). Systematic fieldwork has been carried out in the British

Table 3. Typical field data types and their digital alternatives

<table>
<thead>
<tr>
<th>Field data</th>
<th>Example</th>
<th>Media</th>
<th>Digital alternative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mapping on a field slip</td>
<td>1:10 000 base map</td>
<td>Paper map</td>
<td>Drawing lines on digital base on PDA</td>
</tr>
<tr>
<td>Metadata</td>
<td>Date, weather, location</td>
<td>Paper notebook</td>
<td>Database on PDA</td>
</tr>
<tr>
<td>Observation</td>
<td>Grain size, texture, mineralogy, geometry</td>
<td>Paper notebook</td>
<td>Database entry PDA</td>
</tr>
<tr>
<td>Locality</td>
<td>Grid reference</td>
<td>Paper notebook</td>
<td>Database entry GPS</td>
</tr>
<tr>
<td>Sketches</td>
<td>Outcrop interpretation</td>
<td>Paper notebook or artbook</td>
<td>Digital sketching on a photograph</td>
</tr>
<tr>
<td>Photograph</td>
<td>Outcrop image</td>
<td>Transparency, print</td>
<td>Digital photograph</td>
</tr>
<tr>
<td>Section logging</td>
<td>Sedimentary log</td>
<td>Logging sheets</td>
<td>A digital logging template on PDA</td>
</tr>
</tbody>
</table>
Isles for approximately 200 years, with generations of geoscientists having revisited the same locations, made observations, drawn maps and logged sections. The output from the mapping process (e.g. maps and papers published on a given study area) by necessity provides only an interpretive summary of the primary field data that have been collected during that specific survey. Many of the raw field data remain in field notebooks, field slips and slide collections, and are inaccessible to anyone else who wants to use them. This leads to an enormous amount of replication of expensive data collection each time a new study takes place in any particular location. This cost implication places limitations on the use of field data as a test of experimental or numerical studies of Earth processes. In Britain, this is now recognized in current NERC (Natural Environmental Research Council) policy statements that ‘regard datasets as a valuable resource in their own right’ and ‘requires that recipients of NERC grants offer to deposit with NERC a copy of datasets resulting from the research supported’. The National Geoscience Data Centre (NGDC) provides long-term stewardship of geoscience datasets for onshore UK with a similar facility provided for offshore data. Since the 1990s there have been efforts to agree international standards for geospatial data (ISO/TC 211 and ISO 19100 series) and the definition of a Global Spatial Data Infrastructure. Most major software vendors and the main user groups accept that these standards will provide a framework for the long-term storage of data and will lead to a reduction in expensive primary data reproduction. Digital mapping and survey methods also can be used to standardize field working practices and help to ensure that data collection may be compatible with institutional database formats. We view these developments as a positive step for the long-term stewardship of field data compared with analogue methods whereby data remain hidden in field notebooks and field slips.

Table 4. Compilation of different types of GPS units, their use and an indication of their performance in general fieldwork use

<table>
<thead>
<tr>
<th>Instrument details</th>
<th>GPS units for digital mapping</th>
<th>GPS units for digital surveying</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Garmin III+handheld</td>
<td>Promark 2 (Survey Mode)</td>
</tr>
<tr>
<td></td>
<td>Garmin Geko 201</td>
<td>Trimble 5700/5800</td>
</tr>
<tr>
<td></td>
<td>CSI GBX PRO</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trimble Geoexplorer XT</td>
<td></td>
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<tr>
<td></td>
<td>(built in GIS)</td>
<td></td>
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<tr>
<td></td>
<td>Promark 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>hand held</td>
<td></td>
</tr>
<tr>
<td>Real/time or post-process</td>
<td>WAAS available</td>
<td>L1-carrier wave</td>
</tr>
<tr>
<td></td>
<td>Beacon</td>
<td>L1 &amp; L2 carrier wave + RTK</td>
</tr>
<tr>
<td>Precision tests</td>
<td>WAAS</td>
<td>Post-process</td>
</tr>
<tr>
<td>Number of positional fixes</td>
<td>101</td>
<td>n.a.</td>
</tr>
<tr>
<td>Horizontal Sd (m)</td>
<td>3.42</td>
<td>n.a.</td>
</tr>
<tr>
<td>Vertical Sd (m)</td>
<td>0.16</td>
<td>0.001²</td>
</tr>
<tr>
<td>PDOP during test</td>
<td>1.9</td>
<td>0.003²</td>
</tr>
<tr>
<td>Operational</td>
<td>2 min</td>
<td>0.002²</td>
</tr>
<tr>
<td>Time for position</td>
<td>45 s</td>
<td>&lt;4</td>
</tr>
<tr>
<td>Achievable accuracy</td>
<td>Mapping &gt;100 m scale</td>
<td>c. 30 min observation²</td>
</tr>
<tr>
<td>Purpose</td>
<td>Low</td>
<td>c. 10 min observation²/1 s for RTK</td>
</tr>
<tr>
<td>Cost</td>
<td>£200</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>c. £120</td>
<td>1–10 mm</td>
</tr>
<tr>
<td></td>
<td>c. £1800</td>
<td>for RTK</td>
</tr>
<tr>
<td></td>
<td>Mapping &gt;10 m scale</td>
<td>c. £5000</td>
</tr>
<tr>
<td></td>
<td>Mapping &gt;10 m scale</td>
<td>Mapping &gt;10 m scale</td>
</tr>
<tr>
<td></td>
<td>Intermediate</td>
<td>Intermediate</td>
</tr>
<tr>
<td></td>
<td>0.5–1 m</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>0.5–3 m</td>
<td>0.5–3 m</td>
</tr>
<tr>
<td></td>
<td>1–3 m</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>1–10 mm</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>1–10 mm</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>c. £4000</td>
<td>1–10 mm</td>
</tr>
<tr>
<td></td>
<td>Survey sub-cm scale</td>
<td>Survey sub-cm scale</td>
</tr>
<tr>
<td></td>
<td>c. £25 000</td>
<td>c. £2000</td>
</tr>
</tbody>
</table>

WAAS (wide area augmentation system) provides differential correction data for GPS from geostationary satellites. RTK (real-time kinematic) GPS provides instantaneous positioning to millimetre precision. Inclusion in the table is not an endorsement by the authors of any particular product, n.a., not applicable.

²These figures are calculated accuracy values derived from the post-processing software.

Increased spatial precision of field observations

The precision or error in a GPS position may be estimated by making observations at the same location over a given length of time. The precision achievable by GPS receivers generally varies with cost, which impinges on the possible applications of these units (Table 4). The accuracy (how close the calculated position is to the ‘true’ position) can be determined by making observations on a known survey trigonometric point. Using GPS to locate field data leads to a significant reduction in uncertainty regarding location errors (Maerten et al. 2001). We have benchmarked a range of GPS receivers and found that levels of precision range from 3.5 m to 1 mm (Table 4). Unsurprisingly, precision is largely related to GPS cost, but so too is the functionality built-in to the receiver units. It is clearly important that the unit being used is fit for purpose; for example, it is inappropriate to locate a laser-scanned dataset (with inherent millimetre precision) with a handheld GPS receiver, whereas millimetre precision is not required for most mapping applications. We suggest that for most digital mapping applications, a handheld GPS (e.g. Garmin etrex, Garmin Geko, Magellan eXplorist) will give precision levels that are fit for purpose. Real-time DGPS systems (e.g. Trimble ProXR & GeoExplorer, Leica GS20), which regularly give precision to approximately 0.3 m in the horizontal plane, should be used for detailed mapping applications. For digital survey applications, it is essential to use a survey-grade GPS receiver in which satellite data collected continuously at a base station are post-processed along with the data collected by a rover unit. For rapid acquisition of high-resolution positional data, a real-time kinematic (RTK) GPS is required (Table 4). The positional precision and accuracy that may be achieved using all GPS units is dependent on variations in the input satellite configuration (an
The time it takes to collect the field data. In our experience of
direct line of sight to satellites, steep topography or buildings
can limit the number of input satellites available to a GPS
receiver and degrade, or even prevent, a locational fix. This
means that accurate positioning near cliffs, tall buildings or in
deep valleys may be difficult to achieve. As these are often
situations familiar to geoscientists, it is then necessary to collect
locational data using a laser device or a total station with
reference to nearby fixed points where sight lines to satellites are
not obscured. Another possible source of error known as ‘multi-
path’ can occur when locating near a metallic object (e.g. a chain
link fence) and is due to the satellite signals travelling through
the object before encountering the receiver.

For accurate 3D reconstructions of geological architectures,
the z-coordinate (i.e. elevation) for all positions is essential. Most
mobile-GIS applications allow this to be incorporated into the
data table. Despite GPS having poorer resolution in the z
direction, in good conditions, a DGPS can give a vertical
precision of c. 1–2 m. Alternatively, 2D data may be converted
to 3D by locating the positions on a digital elevation model.
However, the horizontal spacing of the grid nodes (typically
10–50 m) and the precision of the values at each node (typically
±3–10 m) limits the resolution.

Increased reproducibility of results

The ability to reproduce observations and measurements is a
cornerstone of scientific methodology. In the past, it has often
proved difficult to verify another geoscientist’s field observations.
Indeed, the great ‘Highlands Controversy’ of the 19th century
arose in part before systematic mapping had taken place because
different observers had difficulty replicating the observations of
their opponents and could never be sure they were looking at the
same exposures (Oldroyd 1990). Grid references in scientific
papers are given as eight figures at best (more commonly six
figures), so that a given observation is located within a 10 m² or
100 m² grid square. In many cases when mapping in remote areas,
the precision with which a position was located using sighting
compass and field slip is probably only sufficient to warrant the
use of six-figure grid references. Standard compass-based transit
(cross-bearing) methods are not accurate enough to be able to
locate that grid square with confidence so it makes it exceedingly
difficult to revisit old field observations. Digital mapping has
powerful features that improve the capability of one geoscientist
to visit the exact location where an observation was made. This is
because most GPS and DGPS receivers have built-in functions to
navigate back to a stored location. For example, in a blind test a
fault dataset was loaded into a handheld computer and another
fieldworker who had not collected the data used the onboard
mapping program and a real-time DGPS to navigate to a specified
fault sample location. On reaching the position stored in the
database the sampled location was 25 cm north of the fieldworker.
The accuracy level (c. 0.5 m²) is a considerable improvement over
the analogue methods. Real-time kinematic GPS provides even
better (sub-centimetre) precision, meaning that georeferenced
observations can be reliably revisited and re-checked. Thus
arguments about interpretation are less likely to be affected by
uncertainty regarding where exactly the observation was made.

Improved efficiency

The efficiency of fieldwork can be thought of solely in terms of the
time it takes to collect the field data. In our experience of
general digital fieldwork, the time savings made during acquisi-
tion of field data are often marginal when compared with
traditional methods of mapping. However, the inherent digital
nature of the acquired data gives large time savings when
subsequently carrying out detailed analysis (e.g. producing maps,
stereonets, spatial analyses) and producing reports (Maerten
et al. 2001; Jones et al. 2004). For detailed digital survey
applications, however, the time savings are very considerable, but
difficult to quantify. For example, to perform a geospatial analy-
sis of fold structures at Cullercoats (Fig. 3a) took c. 20 h of data
acquisition, but this might take up to 3 weeks (or more) to carry
out using traditional planetabling methods. In such cases it is
unlikely that this type of detailed study would be ever be
undertaken by traditional methods.

Operational efficiency is difficult to assess in a quantitative
manner. On the one hand, PDA units with on-board mapping are
now capable of displaying both raster and vector GIS data at a
variety of scales. Newly acquired field data can then be displayed
along with snippets from large existing databases, leading to an
improved appreciation of the relationship between individual
localities and the regional architectures. Improved 3D display
capabilities for PDAs mean that in the near future the geoscientist
will be able to use 3D displays whilst collecting data. This could
have many advantages when attempting to visualize complex 3D
architectures in the field and may allow better ‘on-the-spot’
hypothesis testing while carrying out the fieldwork. On the other
hand, the complexity of PDA units with on-board mapping means
that the simplicity of paper-based methods is lost and could lead
to a loss of focus on the problem at hand (see below).

Improved understanding of 3D architecture

It is frequently claimed that digital methods can improve our
understanding of 3D architecture (Pundt & Brinkkotter-Runde
2000; Maerten et al. 2001; McCaffrey et al. 2003; Jones et al.
2005). Although the 2.5D perspective views discussed above
allow an improved appreciation of 3D structure in areas of
topographic relief (see McCaffrey et al. 2003), the ability to
work in ‘true’ 3D is essential to those working in many
petroleum, mining and other applied geoscience industries. Here,
the data (drill-hole core and logs, depth-migrated 3D seismic
reflection surveys, etc.) provide precise x-, y-, depth-located (z)
information on subsurface geological architectures. For the field-
based geoscientist, the cross-section (and fence diagram) have
long been the principal tools for depicting the interpreted subsur-
face and above-surface 3D architecture. Both digital mapping
and digital survey methods produce 3D geospatially located data
that can be input into 3D GIS that provide an alternative to
paper-based cross-section drawing methods (Kessler & Mathers
2004). These ‘solid’ models provide a volumetric understanding
of the true 3D significance of the data collected relative to all
other data in the model. New immersive technologies mean that
complex solid architectures are explored from ‘within’ rather
than viewed from the outside (e.g. Fig. 5). Thus digital fieldwork
methods offer the field geoscientist a similar environment to the
industry professional in which to explore and interpret their
datasets, and allow more direct comparisons between surface and
subsurface data to be made (Clegg et al. 2005).

Uncertainty in field data collection

An inherent property of any fieldwork is that the data collected
on a 2D or 2.5D surface occupy a very small part of a 3D
...
volume (i.e. the datasets are sparse in 3D space). To make 3D interpretations from field data it is necessary to reduce uncertainty in 3D volume predictions by using additional control from bore-holes or geophysical exploration (e.g. Pringle et al. 2004; Zeng et al. 2004). Failing this, the volume must be populated by either stochastic or deterministic methods and 3D visualization then becomes a tool in which to visualize the 3D structure of the numerical model and allows validation using field datasets.

In addition to representing an accurate and efficient means of collecting field data, digital mapping techniques open up new possibilities to include an assessment of the certainty or uncertainty associated with the mapping process and using this to evaluate the validity of competing interpretations (Jones et al. 2004; Table 5). In the traditional paper-based approach, these uncertainties are at worst ignored or at best noted in the field notebook. They then tend not to be considered further in the analysis process, and consequently are not available to the end-user. GIS-based data structures provide a means of including geospatially located qualitative statements of uncertainty together with quantitative data (such as precision levels of GPS measurements) in 3D models. Key to this is the ‘solid’ 3D models of the Earth’s architecture explicitly use the geospatially located data in their ‘real’ position relative to all other data in the model. This permits uncertainty statements regarding data quality to be analysed by various logic-based methods and their locations viewed relative to the resulting geological interpretations in 3D. This potentially provides a powerful new method of handling uncertainty in field-based geological architectures.

Field performance and operational issues

The cost of robust, weather-resistant equipment is still relatively high (although prices are falling rapidly). Handheld computers (PDA) are largely designed for office and personal use, although with care they may be used in the field (Wilson et al. 2005). Cheaper equipment is generally not robust enough for long-term use or expedition fieldwork.

Developments in battery technology have played a key role in the usability of digital geological mapping and survey equipment. Lightweight, long-life rechargeable batteries are required to power handheld computers and GPS equipment. Typically the fieldworker will get a maximum of 6–8 h use from most units, meaning that extra power cells are required for long days. Recharge times must be taken into consideration when planning fieldwork, particularly when camping. Wireless communications protocols now allow field units (GPS, PDA) to transmit data to each other and transfer files to lap-top and desk-top computers, and thus remove issues associated with cables and connectors between the various parts of the equipment.

There is always potential for data loss or corruption in the event of equipment failure so a systematic data back-up strategy is essential. Loss of a complete digital database that has not been backed-up is just as disastrous as losing a full field notebook. It is relatively easy to copy data to a lap-top at the field base each evening; in contrast, it is relatively difficult to routinely back-up a field notebook!

The physical size and weight of the amount of equipment that must be carried is another major consideration. Digital geological mapping systems are relatively compact and portable and will fit onto or into a small rucksack. Digital survey equipment, such as RTK GPS systems and laser scanning equipment, is bulky and is not easily transported far from a vehicle, placing limits on the outcrops that may be surveyed at high resolution.

Many of the core technologies for both digital geological mapping and survey are not currently fully integrated with one another, so that workflows for digital mapping are not fully

Table 5. Types of uncertainty encountered in geoscience fieldwork (from Jones et al. 2004)

<table>
<thead>
<tr>
<th>Type of uncertainty</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data acquisition Positional</td>
<td>‘How sure am I of my current location?’</td>
</tr>
<tr>
<td></td>
<td>‘How reliable is my base map?’</td>
</tr>
<tr>
<td></td>
<td>‘What is the precision of my GPS measurements?’</td>
</tr>
<tr>
<td></td>
<td>‘Is the borehole straight, or has it deviated without me knowing?’</td>
</tr>
<tr>
<td>Measurement</td>
<td>‘What is the precision of my clinometer?’</td>
</tr>
<tr>
<td>Scale-dependent variability</td>
<td>‘What is the accuracy of my dip and strike readings?’</td>
</tr>
<tr>
<td></td>
<td>‘How much does the dip and strike vary over the scale of the outcrop?’</td>
</tr>
<tr>
<td>Observational</td>
<td>‘Is this rock best described as a granite?’</td>
</tr>
<tr>
<td></td>
<td>‘Is this fossil the brachiopod Pentamerus?’</td>
</tr>
<tr>
<td></td>
<td>‘Is that a stretching lineation or an intersection lineation?’</td>
</tr>
<tr>
<td>Temporal</td>
<td>‘How reliable is this way-up criterion?’</td>
</tr>
<tr>
<td>Sampling bias</td>
<td>‘Is the relative age of these structures identified correctly?’</td>
</tr>
<tr>
<td></td>
<td>‘Are my data biased by the natural predominance of subhorizontal exposures?’</td>
</tr>
<tr>
<td>Primary interpretation</td>
<td>‘Is this limestone the same unit as the limestone at the last outcrop?’</td>
</tr>
<tr>
<td>Correlation</td>
<td>‘Is it valid to correlate the S2 fabric here with the S2 fabric observed on the other side of the area?’</td>
</tr>
<tr>
<td>Interpolation</td>
<td>‘How likely is it that all the ground between these two outcrops of slate also consists of slate?’</td>
</tr>
<tr>
<td>Inference from topography</td>
<td>‘Does this sharp change in slope correspond to a lithological boundary?’</td>
</tr>
<tr>
<td>Compound interpretation</td>
<td>‘How can I quantify the uncertainty associated with this sophisticated interpretive model that I have slowly built up through a long iterative process of data collection and individual primary interpretations!’</td>
</tr>
<tr>
<td>Finished 2D map</td>
<td>‘Does there really a fault running along the unexposed valley floor?’</td>
</tr>
<tr>
<td>Geological cross-section</td>
<td>‘Is my reading representative of the surrounding area?’</td>
</tr>
<tr>
<td>3D structural model</td>
<td>‘How reliable is my base map?’</td>
</tr>
</tbody>
</table>
problems remain with compatibility of hardware and software, and with different data formats required between successive stages in the workflow from field acquisition to visualization and analysis. Software vendors are attempting to use more ‘open’ formats or are providing tools that allow data to be converted from one format to another, although there is still a long way to go until the process could be described as ‘seamless’.

### User resistance and demise of mapping skills

Most geoscientists will initially find traditional fieldwork methods easier to use than the digital alternatives because they are familiar with these from their undergraduate training. This distinction is much less marked with recent undergraduates (i.e. those born in the 1980s), for whom digital devices have always been a central aspect of their educational and social environments. With any technological advance there will always be a section of the user community who would prefer to continue with the old tried and tested methods. There are also concerns that there will be a demise of generic mapping skills. However, we feel that most of the important skills, such as observation, interpretation, analysis and continuing hypothesis testing, that would be expected from an experienced and talented fieldworker should be enhanced by using digital methods. For example, the ability to plot an instant stereonet in the field, call up an old dataset, or see how a contact mapped at one particular locality would project through the whole field area, must enhance the interpretation process. There could be a loss of cartographic skills in the sense that there would no longer be a need to use pencils, mapping pens and colouring pencils, but these can be regarded as mechanistic rather than generic mapping skills. A parallel example was the transition from hand-drafted to computer-drawn figures in the past 15 years. Admittedly, in the first few years, computer-drawn diagrams were crude and not aesthetically pleasing, but now almost all published diagrams are computer drafted and the standard is generally equivalent or better than before. With improved accessibility to mapping technology, expertise in fieldwork will not be restricted to people with good artistic skills. Nevertheless, we emphasize that it is important that undergraduates are still trained in traditional paper-based mapping methods so when the batteries run out or there is no satellite coverage they can still function in the field.

The publication of colour 3D diagrams impinges on digital geological mapping and survey practice. Three-dimensional models are best viewed on a computer screen because features may need to be coloured differently, and the ability to move the model relative to the viewer’s eye gives an important depth perspective to the model. Problems arise when trying to publish these models, as most journals still have a paper-based format and publishing diagrams in colour is expensive. Journal publishing houses are launching electronic publishing formats that can display colour 3D diagrams and animations along with hyperlinked images and text. These initiatives will allow 3D models produced by geoscientists using digital mapping and survey methods to be published with equal merit alongside traditional papers.

### Unlocking the spatial dimension

We suggest that the adoption of digital fieldwork practices will provide the geoscientist with significant advantages. The increased spatial accuracy of field data allows methods of geospatial analysis and geostatistics to inform hypothesis testing during fieldwork. Three-dimensional models of geological architectures can be based on ‘real’ data locations rather than abstractions or schematic representations based on the geoscientist’s ‘mind’ model. Robust estimates of uncertainty in field data can be carried forward to become explicit in published 3D models. Other advantages include better data management on projects, with much better reproducibility of observations, and the ability to carry pre-existing data into the field to provide supplementary information to aid data collection, interpretation and hypothesis testing. All data-types can now be integrated into a single geospatially referenced database to institutional and/or agreed national or international data standards. It is now feasible to implement a more streamlined digital workflow from the initial data acquisition stage to the final project output.

The main disadvantages of digital fieldwork methods are the associated equipment costs, which mean that digital methods are not, as yet, suitable for routine use by undergraduates. The equipment is bulky whereas cheaper equipment is not very robust; also, it requires a lot of battery power, cable connections and IT skills. It is to be expected that there will be user resistance in the community, and possibly some demise of traditional cartographic skills may be anticipated. All of these issues are expected to diminish as new technologies and methods are introduced into mainstream fieldwork.

In 5–10 years time, we predict that digital mapping and survey systems will be much easier to use, more streamlined physically, durable, with long-life batteries and wireless connectivity. Extensive analysis software will be available in the field on handheld devices. The iterative interpretation cycle will be shortened and will possibly take place largely on the outcrop. Three-dimensional autostereo screens will be available on PDAs and flexible foldable large screens will allow field-based visualization and interpretation of large models. Fieldwork may become more dynamic: remote databases could be updated on the fly via a wireless link from a computer at base, and this would permit the undertaking of live sensitivity analysis on field-based 3D models. Common repositories of field data will be developed so that field geoscientists can make use of, and add to, a common body of geological field data, rather than having only their own notebook. Reliable voice recognition capabilities added to field devices will make the transition from field notebook to electronic database easier. Software advances will allow more ‘semantic’ based collection of field notes (Jones et al. 2004), and prior information will be recorded and distinguished from new data and incorporated into 3D models and used to estimate uncertainty.

We posed the question in the introduction as to whether the acquisition, visualization and analysis of high-resolution digital geospatial field databases will revolutionize the Earth Sciences. A perhaps not totally unbiased answer from this study is yes. There is an enormous potential to be gained from unlocking the spatial dimension in geoscience fieldwork. The underlying philosophies and technologies will no doubt take some time to become widely accepted and universally used. We suggest, however, that digital fieldwork methods and their underlying geospatial databases will be the new ‘standard tool’ for geoscientists and may well prove to be as durable as the geological map has been to our 18th- to 20th-century ancestors.

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