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Archaeological Informatics: Beyond Technology

Remote Sensing and Geophysical Prospection

by Armin Schmidt

Abstract

In archaeological prospection computer processing is essential for all stages of data manipulation. This article investigates the contributions which informatics has made in the past and looks at its potential for the future. It is shown how the workflow of satellite imagery, aerial photography and geophysical prospection can be broken down into measurements, acquisition, processing, visualisation and interpretation. Based on these categories, the advantages of digital data manipulations are explored with individual examples. It is shown that informatics can greatly assist with the final archaeological analysis of the measurements but that human experience and assessments are crucial for a meaningful interpretation.

0. Introduction

Archaeological prospection methods have become an integral part of the archaeologists' toolbox. In fact, geophysical surveys are now seen as a commodity, being regularly used for site assessment, either in their own right or as part of an integrated prospection strategy. Computers are required to manipulate the volume of resulting data so that geophysical techniques and informatics have become inseparably intertwined. It is therefore useful to analyse the role of informatics in archaeological prospection, investigate its contribution to past developments and explore possible future directions. The following text will discuss the use of computers in aerial photography and satellite imagery (summarised as 'remote sensing'), as well as geophysical prospection.

1. Informatics in Archaeological Prospection

The purpose of archaeological prospection is to collect data that can be used for the non-destructive investigation of buried archaeological remains. The processes leading to this end can be subdivided into different stages, which all require computer manipulation of data.

i) **Measurements and data recording**: While an excavator is guided by variations in soil colour and composition, remote sensing and geophysical surveys detect contrasts in those soil properties that are not recognised by humans (e.g. electrical resistance, magnetic susceptibility). Similarly, aerial photographs allow perspectives of sites, which are not otherwise available. In addition, a large volume of information is recorded for further analysis and often stored digitally.

ii) **Acquisition procedure**: The way data are collected is partly influenced by the method used (e.g. air photography) and partly by the data handling and manipulation (e.g. gridded geophysical data).

iii) **Data processing**: Computer processing can help to amplify significant features in the collected data if the chosen mathematical operators respect the nature of measurements (e.g. perspective distortion of oblique photographs, complex magnetic signals of simple features).

The efficient implementation of these operations as computing algorithms is often challenging.

iv) **Visualisation**: The visualisation of results can range from a photographic print to a virtual reality exploration of data, with various degrees of computer manipulation.

v) **Interpretation**: The final archaeological interpretation of prospection results requires considerable understanding of the characteristics of used data and of the underlying archaeological remains. Appropriate computer technology can assist such interpretation.

While a separation of archaeological prospection into these five stages is useful for analysis, it has to be remembered that they are all interrelated. For example, interpretation requires visualisation, which in turn is dependent on meaningful data processing. The acquisition procedure, on the other hand, can depend on the available visualisation techniques and on the level of interpretation that is required as a final result.

2. Remote Sensing

2.1 Measurements and data recording

In many cases the availability of data governs the archaeological questions that can be resolved. Nevertheless it is useful to consider the principles underpinning remote sensing imagery to identify requirements for data recording and digital storage. Most archaeologists use aerial photographs to identify individual features and the detail visible on conventional photographs is sufficient to resolve even small anomalies. It is the high spatial resolution of these images that allows such ‘specific’ use. In contrast, satellite scenes have suffered for a long time from a much coarser resolution but instead offered ‘synoptic’ information through broad overviews of landscapes or multispectral data for the classification of the ground’s cover.

The high spatial resolution of aerial photographs can be attributed to two factors: The relative low height of recording and the use of photographic films as medium for 'data storage'. The disadvantage of the former is the concentration on specific features with the consequent lack of a synoptic overview, while the use of analogue recording media necessitates an additional processing step before digital data are available for computer manipulation. This processing can either be accomplished by scanning of negatives and prints, or by manually digitising individual features identified on photographs. Using digital cameras would eliminate this intermediate step and facilitate long-term archiving without degradation of quality. However, to achieve an image quality that is comparable to photographic film, further improvements in the resolution of digital cameras and the storage of the large resulting data volumes are required. While it is always commendable to collect primary data with the highest possible quality (e.g. high resolution on photographic films), the much simpler handling of digital images must also be considered. It will be interesting to see how much further digital imaging has to develop before it becomes the primary recording tool.

Ground resolution of satellite images has improved considerably over the years. In 1986 the first SPOT satellites were started and delivered data with 20m and 10m resolution for multi-spectral and panchromatic scenes, respectively. Later, the Russian KVR-1000 satellite amazed users with panchromatic images of about 2-5m resolution and the launch of ICONOS in September 1999 made satellite images available with just 1m small pixels (Fowler 2000). It has therefore become possible to use satellite images for the specific identification of archaeological features. It should be noted that the impressive improvement of satellite imaging sensors was only feasible with the simultaneous development of computer systems, capable of handling the increased amount of data.

The limited resolution of satellite imagery has often been compensated for by the availability of multispectral data. By recording the intensity of reflected electromagnetic radiation at various wavelengths for each measured pixel, it is possible to characterise ground features (e.g. grass *vs.*

wheat). Such synoptic approach allows new insights into an archaeological landscape beyond the identification of individual features. A good example is Fowler's (1994) investigation of the area around Stonehenge where he was able to identify different types of grass covers in individual fields from LANDSAT TM multispectral data. The implications for heritage management are significant and similar applications to the wetlands of Cumbria also showed promising results (Cox 1992). Multispectral sensors mounted on aeroplanes achieve high spatial resolution, and early applications for the investigation of ancient Maya canal networks appeared very promising (Adams 1980). More recently, the air-borne CASI sensors (Compact Airborne Spectrographic Imager) have opened new avenues for archaeological applications (Holden 2001). The development of improved multi-spectral systems was fuelled by the great success of computer-classifications, showing again the important contributions from informatics.

Most remote sensing techniques are passive as they only record the electromagnetic radiation, which is naturally reflected from the ground. In contrast, synthetic aperture radar collects data actively. A beam of high frequency electromagnetic waves (above 1GHz) is emitted from the air- or space-borne system and the returns are recorded. 'Synthetic aperture' describes the enhancement of sensor resolution by using the overlapping returns along the flight path to construct a more focused image (Rees 1990: 159). These systems possess two major advantages, namely a defined reference signal and a potentially higher depth penetration.

The primary radar waves are transmitted with a known timing to which the received signals can be related. The recorded data therefore contain not only amplitude (i.e. intensity) but also phase information. If scenes from two adjacent flight paths (or from two tandem sensors) are recorded, these paired images can be overlaid to produce interferences or 'fringe patterns', similar to a hologram. Each fringe corresponds to a contour line and after advanced computations, detailed topographical maps can be created. The height accuracy is determined by the wavelength of the radar signals. It should be possible to design air-borne high frequency interferometric radar systems that allow the remote mapping of archaeological sites at reasonable horizontal and vertical resolution to calculate detailed digital terrain models (DTMs) that are akin to ground based earthwork surveys.

Another advantage of the active nature of radar imaging is the possibility to observe the polarisation of the received electromagnetic waves. This information is already used for the characterisation of some targets (e.g. trees *vs.* buildings) but its potential has not been fully realised in archaeology. The advanced processing of relevant radar data could help to automatically identify classes of archaeological features (e.g. grass covered earthworks *vs.* standing remains).

Radar waves have a shorter wavelength than optical light and can therefore penetrate deeper into dry ground. This has been shown with data from the Spaceshuttle-borne SIR-B sensors that revealed palaeo-rivers underneath the Southern Egyptian Sahara (McHugh *et al.* 1988). When excavating alongside the shores of these 'radar rivers' a large number of Acheulean stone tools were found, confirming the potential of the method for site prediction. The potential of radar waves to penetrate about 1.5-2m into dry ground may help to reveal even structural archaeological remains that are covered by sand if high resolution air-borne sensors are used.

Another method for the creation of DTMs is the use of air-borne laser ranging equipment (LIDAR). The early tests for archaeological applications were disappointing (J. Orbons *pers. com.* 1999) but later results showed some promise with height accuracies of about 0.1m and the possibility for a spatial resolution better than 1m (Holden 2001). A combination of laser ranging data with stereo-pair images (see below) may allow a considerable enhancement of results.

2.2 Acquisition procedure

Of great importance for any archaeological use of remote sensing images is their appropriate georeferencing or rectification. Only in this way is it possible to relate them to archaeological features on the ground and to combine them with other data in a GIS, for example with geophysical results. Satellite images are increasingly delivered in a georeferenced format that clearly specifies their location. Since most of them were taken vertically, distortions due to changes in topography are considered to be small so that a simple affine transformation is deemed sufficient. However, only the position directly underneath a sensor is recorded vertically and areas away from this position may be distorted by the undulating landscape. There is therefore a market for photogrammetrically rectified remote sensing data based on accurate topographical maps, so called ortho-photographs. Software to produce such results is available and it can be expected that data will increasingly be delivered with these corrections applied.

The situation is more complicated for aerial photographs, which in many instances are taken from an oblique angle from a small aircraft. With the reduced costs of in-flight GPS equipment it has become possible to assign well-defined coordinates to each photograph taken. However, these coordinates only refer to the camera position; the targeted archaeological feature may lie somewhere in the area around it. To provide more accurate information for the target location, various solutions are conceivable. Due to the continuous recording of the aircraft's GPS coordinates, its orientation can also be determined (e.g. "flying due north"). If some information on the relative orientation between camera and aircraft is available, the position of the photographed target can hence be estimated. Such information can either be a vague verbal description (e.g. "through right window, looking straight ahead") or a mechanical link between the two systems that measures two angles accurately. Alternatively, it is conceivable, to obtain an absolute record of the camera direction using an attached digital compass. Together with the aircraft's GPS coordinates the target location can then be calculated.

The continuous recording of flight-path coordinates is also an essential aid in large scale recording campaigns, like the English Heritage funded National Mapping Programme (Bewley 2001). The incorporation of such information into a GIS allows to allocate flying resources to the least investigated areas.

2.3 Data processing

Once remote sensing data are available in digital format, computer processing can be used to enhance small variations related to archaeological information. Most modern image manipulation software, even including some freeware packages (e.g. www.irfanview.com), contain image enhancement routines that can be applied to remote sensing images. It is important to remember that such processing may in some cases improve feature definition but cannot replace high-quality input data, for example aerial photographs taken with good cameras and films.

The most important processing of remote sensing data is their rectification and georeferencing. Based on control points identified in an image and on maps, photogrammetric calculations project the data onto a base map. To achieve high accuracy, topographical data must be considered in these calculations (Doneus 2001) and a number of software packages are available for aerial archaeology, most notably Aerial (Haigh 2000) and AirPhoto (Scollar 1998). As with all archaeological prospection techniques, interpretation of the original data is required and there is some discussion of whether interpretations should be carried out on the original oblique image and then rectified in the same way as the photograph (Palmer 2000), or whether interpretation diagrams could be based on rectified images alone. The former approach has the advantage that break lines and shadows can be identified more easily, while the latter method is less time consuming and allows to base interpretations on actual feature shapes (e.g. otherwise distorted circular ditch systems).

The distortion of images due to undulating topography can be exploited for their three-dimensional analysis. If vertical remote sensing scenes (satellite- or air-borne) are collected with considerable overlap, or oblique aerial photographs are taken from two close positions, pairs of such images can be used to view the results in three-dimensions with an optical stereoscope or to analyse them with a stereo-plotter. If the paired images are available in digital format they can be used to compute topographical models. However, most of the commercially implemented algorithms require considerable user input and information about camera position, direction and calibration, as well as ground control points. For many archaeological aerial photographs, such information is not easily available. Redfern *et al.* (1999) developed a new algorithm for individual archaeological monuments (i.e. only small areas of a photograph) that requires only limited user input. The accuracy of a resulting DTM is about 0.9m and it is hoped that further improvements will make this technique a cost-effective alternative to ground-based topographic recording.

While multi-spectral images are clearly desirable for feature classification (see above), the complexity of necessary sensors leads to coarser ground resolution than for panchromatic (i.e. ‘black-and-white’) data. To overcome this limitation it is possible to compute higher-resolution multi-spectral scenes using interpolation schemes that are guided by the panchromatic images with higher resolution. It is therefore necessary that both data sets are spatially matched with very high accuracy. The interpolation algorithms are sophisticated and not yet widely available. However, with high-resolution multi-spectral images produced in this way, it will be possible to classify individual archaeological features based on their spectral characteristics (e.g. walls or ditches). In contrast to conventional remote sensing applications (e.g. determining agricultural crops or ground covers), it may be necessary to include information on the surrounding areas into the classification algorithms. This would help to identify, for example, wilted parch marks on grass and early ripened crop-marks in wheat both as signatures of buried walls, despite the different moisture levels in the respective vegetation and hence different spectral signatures.

2.4 Visualisation

Beyond the common plan-view visualisation of remote sensing images it can be expected that a computerised replacement for the use of stereoscopes can be found. If DTMs are available, for example calculated from stereo-pairs, data can be visualised as virtual reality models and stereo-projection can help to interpret subtle features. Such visualisation will help archaeologists to interpret remote sensing data by representing them in a naturalistic way.

2.5 Interpretation

The final goal of any remote sensing investigation is the archaeological interpretation of detected features. Information is therefore required on the underlying archaeological landscape and shapes of potential archaeological features as well as a thorough understanding of the visible anomalies. The latter can be greatly assisted by computer applications, using image enhancement, feature extraction or multispectral classification. However, the final interpretation will have to rely on human interpreters who can include ‘fuzzy’ archaeological knowledge for a convincing analysis.

3. Geophysical Prospection

3.1 Measurement and data recording

The development of geophysical instrumentation is closely linked to the rapid improvement of data recording hard- and software. Only the copious storage capacity and convenient operation of the latest instruments have made the geophysical prospecting of large areas possible. Even a small Ground Penetrating Radar (GPR) survey can produce gigabytes of data that are only manageable with modern computing equipment. Prevailing survey procedures pertinent to different geophysical disciplines also had a profound influence on the design of data loggers. Geophysical surveys for geological purposes tended to be carried out along long lines that were fairly widely spaced. Accordingly, data recording is undertaken with line and point numbers stored individually for each data point. In contrast, archaeological geophysical surveys are usually carried out on a regular sample grid and the position of a specific measurement is hence determined by counting all readings from the start of a grid. These different frameworks of data recording are perpetuating themselves, as practitioners who are used to one system are often reluctant to adopt instruments that use a different method of data logging.

With the miniaturisation of computing devices the intelligence of data loggers has increased dramatically. LCD screens that show trace plots as the operator walks along a line are already implemented and greyscale displays that fill as a survey progresses have been suggested (M Noel, *pers. com.* 1999).

3.2 Acquisition procedure

As outlined above, it has become common practice to record archaeological magnetometer and earth resistance surveys on a regular grid (e.g. 0.5m × 0.5m) as an even and unbiased coverage can be achieved and gridded data can be handled very efficiently during storage and processing. It has become obvious in recent years (Becker 1995, Neubauer and Eder-Hinterleitner 1997, Schmidt and Marshall 1997) that higher sampling resolutions bring significant benefits for the interpretation of geophysical data. Not only can smaller archaeological features be detected (e.g. Fassbinder and Irlinger (1994) were able to identify individual postholes) but the overall interpretation of data is improved as the full geophysical signature of anomalies becomes apparent. Small-scale magnetic anomalies may reveal themselves with clear dipolar signatures rather than being reduced to a single high reading at lower spatial resolution. Based on such improved resolution, Norton and Witten (1998) proposed an algorithm to remove magnetic dipole signals from magnetometer data, caused by small ferrous contamination. The advent of multi-sensor arrays (Becker 1999) made surveys of 0.25m × 0.25m feasible.

An entirely different approach is the acquisition of data while walking randomly. ‘Scanning’ describes a method where the operator continuously assesses the readings of, for example, a magnetometer while walking over a field and dropping markers on the ground where the readings ‘seem to warrant it’. The results are not strictly reproducible, very subjective and depend strongly on the skills of the operator. The data cannot be analysed further and important, but weak, features may easily be missed (Gimson 2001: 25). It is therefore not a recommended technique! If undertaken more scientifically, the position and reading of an instrument carried over a site can be recorded continuously. This method produces data maps that are comparable to conventional survey results. However, the sampling density of such surveys is not uniform, with a high resolution along the line of walking but larger, and irregular, distances between such lines. It is crucial to preserve information on this sampling regime to assess resulting maps. Simple interpolation to a regular grid may therefore be unsuitable. Sauerländer *et al.* (1999) suggested to use Delaunay triangulations and their associated Voronoi diagrams for mapping, which corresponds to the use of Nearest Neighbour interpolation on a fine grid (e.g. 0.05m × 0.05m). The resulting polygons honour the original sampling regime. If smooth transitions between data values are required (i.e. interpolation) Natural Neighbour gridding can be used to remove data mismatch at polygon boundaries (Li and Götze 1999).

The position of the geophysical instrument can be recorded accurately with differential GPS (Sauerländer *et al.* 1999) but the necessary equipment may influence very sensitive magnetometers. This data acquisition method avoids the laying out of predefined grids (e.g. 20m × 20m) in advance of a survey, considerably reducing the overall time spent on a site. However, a drawback is the uneven sampling and the potential to miss small anomalies. Sauerländer *et al.* (1999) suggested to evaluate results continuously and send a surveyor back to interesting, but under-sampled locations to acquire additional data. Clearly, this relies on subjective judgement. A prerequisite for such approach is the instantaneous data visualisation during a survey. Data can be transmitted to a base station where powerful computers continuously recalculate the Delaunay triangulation for each new measurement point.

If measurements are recorded only at large intervals, sampling strategies should be selected carefully. For example, magnetic susceptibility surveys are often undertaken with very sparse sampling (e.g. every 20m) and the validity of this approach needs to be investigated. As with any other sampling technique, the intended use of resulting data determines the design of the strategy. In contrast to geochemical measurements, enhanced magnetic susceptibility does not normally diffuse in soil but often varies strongly even over small distances (e.g. over a fireplace). Interpolation of data can therefore only be justified if the soil has been mixed and spread, for example by ploughing. It is hence important to consider whether interpolation of sparse data is appropriate or whether a denser sampling regime is required. It is anticipated that geostatistical methods will be used to assess the validity of certain sampling regimes (Dabas 1999). While the underlying sampling resolution is of crucial importance, the choice of an interpolation algorithm for the resulting data is far less critical.

3.3 Data processing

A large number of algorithms are available to 'process' geophysical data. It is therefore useful to investigate carefully which data are used, and what processing is possible and necessary. A differentiation into three categories has proved to be useful (see Fig. 1).

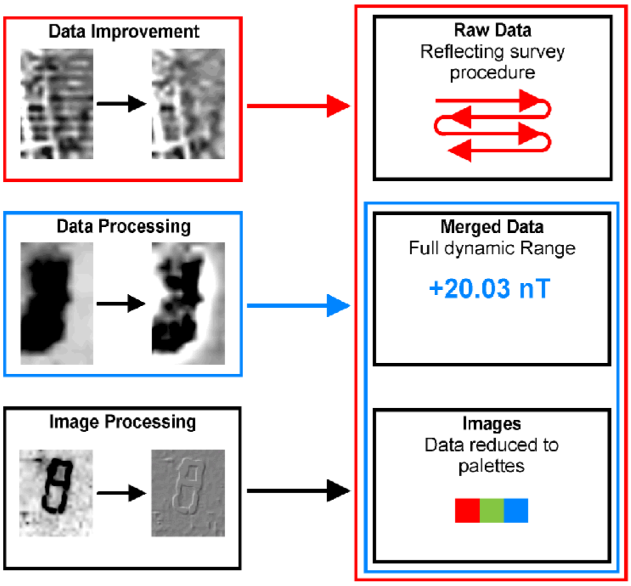

Figure 1: Three different categories of data processing, requiring corresponding levels of detail in the data.

Data Improvement: Where information on the method of data acquisition is available, common data acquisition problems can be rectified with appropriate algorithms. For example, data collected while walking up and down a field ('zig-zag') sometimes show staggering ('shearing') between adjacent lines, due to misalignment of the operator with the predefined grid. If the length of individual survey traverses and the order of zig-zag lines are known the problem can be partly corrected. Such processing can only be applied if data are available in a format that reflects the surveying procedure (e.g. if data are saved as separate grids) and if information on the surveying strategy is given (e.g. "zig-zag lines within each grid, starting in the NW corner"). Other examples of data improvements include zero-drift correction and grid balancing.

Data Processing: Where the full dynamic range of measurement values is available, processing algorithms can be applied that are suitable for the particular geophysical technique used (e.g. reduction-to-the-pole for magnetometer data or high-pass filtering of earth resistance data to bring out small scale variations; Fig. 2). To avoid problems at the boundaries between individual sections of data (grids) they are often merged into one single 'composite' before such processing is carried out. It is essential that information on the spatial dimensions of the data (e.g. resolution) is available and for combination with other data sources the coregistration of the geophysics grid system is required.

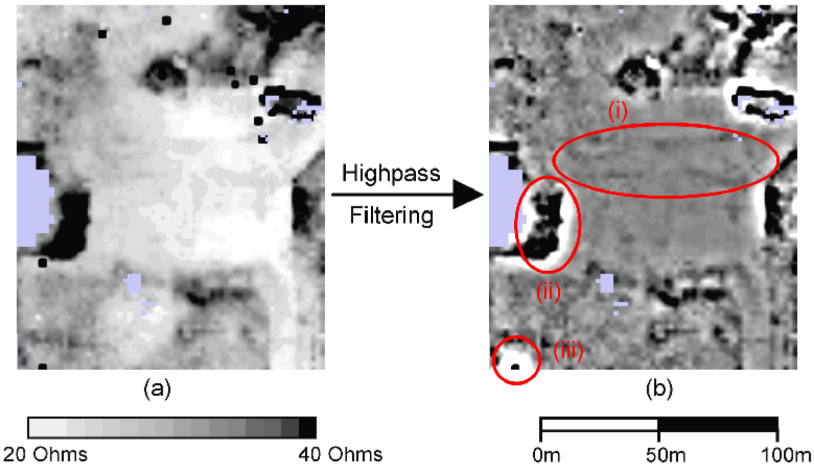

Figure 2: High-pass filtered earth resistance data from the courtyard of a Buddhist monastery at Paharpur, Bangladesh. (a) Raw data and (b) filtered data showing the buried remains of two walls (i) and processing artefacts (ii) and (iii).

Image Processing: When data are converted into images for display purposes, accurate spatial information is often lost and the full range of data values is compressed to the limited resolution of a palette that suits a particular display best (e.g. 256 shades of grey). These pictures can then only be treated with standard image processing tools that do not take into account the geophysical nature of the underlying data. A typical example would be ‘embossing’ or ‘blurring’ that can create pleasingly looking pictures that have, however, limited analytical use.

There have been various advances in ‘data improvement’ techniques, for example the development of sophisticated destaggering methods (Eder-Hinterleitner *et al.* 1996), but the following will focus on ‘data processing’ as defined above. The main purpose of such processing is the discovery of information that is encapsulated within the data but cannot be ‘seen’ if they are displayed in a conventional way. In some cases, more imaginative visualisation techniques will bring out subtle features (e.g. animation, see below) and sometimes the inspection of different clipping ranges is sufficient to gain new insight (Vernon *et al.* 1999). However, suitable processing is often the only way to discover relevant archaeological anomalies. A good example is high-pass filtering where a background (presumed to be a geological ‘trend’) is removed from the data to reveal small-scale features, which are taken as the desired archaeological remains. However, such filtering introduces new artefacts into the data, most notably halos around confined anomalies (see Fig. 2). It is hence of paramount importance to be aware that such signatures are caused by the inherent properties of a particular processing technique and are not ‘real’. The danger is obvious: when the processing is more complex and the whole algorithm is seen as a ‘black box’, it becomes difficult for the user to distinguish between archaeological anomalies and processing artefacts. Modern software packages fortunately offer large numbers of processing functions (Schmidt 2001) but if applied in random order by a novice user they can produce meaningless results. Comparison with the original measurement data is therefore always recommended and some authors suggest to minimise processing altogether (Gaffney *et al.* 1991) by collecting data of highest quality in the first instance.

3.4 Visualisation

Visualisation is used to display recorded data values in a way that can be easily understood by an interpreter. It is important to maintain the spatial characteristics of underlying measurements so that the morphology of archaeological features can be recognised.

Although geophysical data are recorded at individual positions ('point data'), they are affected to a larger or smaller degree by all features and soil in the vicinity. For sampling intervals up to about 1m, measurements can therefore be displayed as raster data, where each value is represented by a rectangular cell. It is filled with a colour or shade of grey from a palette, according to a predefined transfer function or look-up-table. By altering the parameters of this transfer function (e.g. upper and lower clipping values, contrast) different features can be highlighted. Some software packages (e.g. Fortner Software's 'Transform') allow to 'fiddle' (sic!) with this display by adjusting range and contrast according to the two-dimensional movement of a mouse pointer on the computer screen. Other display modes are also in use and line diagrams ('x/y plots') that show data as traces along the lines of survey are often requested (David 1995: 32).

To avoid artefacts often introduced by processing techniques (e.g. halos of high pass filters, see above) new methods of visualisation can be employed for the exploration of data. Cheetham (1996) introduced animation of geophysical results as an alternative to high-pass filtering. When displaying earth resistance data as a rapid sequence of images with narrow but overlapping clipping ranges, the human observer maintains an 'impression' of features that are visible in subsequent frames while a smoothly varying background is suppressed. In this way, weak anomalies on a gradually changing background can be identified. Such techniques do not lend themselves to paper-reproduction but have clear benefits and are already used on some Web pages (Marshall 1998).

Most geophysical techniques are used to create two-dimensional horizontal data maps, as these are similar to plan-views of an excavation and allow assessment of archaeological remains based on the features' shape. With GPR it has become possible to collect data in three dimensions by acquiring many parallel lines ('2D sections') to form a 'data cube'. Techniques for its processing and visualisation, however, have been developed only in the last few years (Conyers and Goodman 1997). In contrast to other geophysical techniques, GPR data only show interfaces and are not directly representative of a feature's properties. In this respect they are akin to first order derivatives and require sharp changes of dielectric permittivity in the ground (e.g. between soil and stone). However, Leckebusch and Peikert (2001) have shown that 3D migration techniques, originally developed for seismic data, can be used to derive a soil parameter called 'reflection strength' even for the interior of features and for gradual transitions between dielectric permittivities. This parameter hence represents the volume of buried features, and not just their horizontal interfaces. As such it lends itself to three-dimensional visualisation.

The easiest approach is to produce time-slices as 'horizontal' maps averaged over limited reflection time intervals (for example, Camerlynck *et al.* (1994) averaged over 5ns). They often show depth variations of features very well, especially if they are displayed sequentially with animation software. However, the time slices themselves are still two-dimensional and it is difficult to fully appreciate the stratigraphic and spatial relationships between different features, especially if they are tilting. Hence, data need to be visualised in three dimensions, using virtual reality models and stereo projections. A prerequisite is the calculation of 'reflection strength' for the whole ground volume, based on the measured reflections from horizontal interfaces (see above). Leckebusch (2001: 63) showed that subsequent conversion into iso-surfaces is required to compress the large data sets and allow for their real-time 3D exploration.

Magnetometer surveys are far less suited for 3D imaging, simply because at each position only one data value is measured, equivalent to recording a single layer. It is therefore possible to assume various feature arrangements with different magnetic parameters that would all produce the same measured values at the surface. Magnetic inversion has hence no unique solution (Blakely 1996: 217). However, if some prior information is used, for example the typical shape of a Roman ditch, or values of magnetic susceptibility of plough soil, subsoil and bedrock, a constrained inversion algorithm can be constructed that often produces very realistic information on the three dimensional layout of buried archaeological features. Neubauer and Eder-Hinterleitner (1997b) used leaped annealing to calculate 3D models of Neolithic circular ring ditches, which were discovered with magnetometer surveys. These reconstructed models not only helped with the archaeological understanding of geophysical anomalies but also revealed the plough damage to these monuments more clearly than the original data. Dittrich and Koppelt (1997) used genetic algorithms and Herwanger *et al.* (2000) iterative least-square inversion with considerable prior assumptions to achieve similar results.

3.5 Interpretation

Standard processing techniques, like high- and low-pass filtering, or the reduction-to-the-pole of magnetometer data (Blakely 1996: 330), use the original measurements to calculate new data maps that can be interpreted more easily as archaeological features. Such interpretation therefore requires a profound understanding of the measurements' geophysical nature. For example, in magnetometer data a positive peak with an adjacent negative trough should not be interpreted as two separate features (e.g. 'rampart and ditch') since such geophysical anomalies are normally caused by just one single entity. To simplify the archaeological interpretation 'complex attributes' can be calculated. Tsokas and Hansen (2000) showed how magnetometer data are used to calculate new parameters (e.g. 'depth to interface', magnetic susceptibility) that simplify interpretation by including the geophysical knowledge in an algorithm and provide a more user-friendly output. When taking this idea further, algorithms for 'automated interpretations' can be devised. Sheen (1998) showed how a hybrid artificial neural network is used to locate significant features in magnetometer data and estimated their depth and width. Comments about the dangers of a 'black box-approach' apply even more to such methods. The best solution might be for a skilled operator to compare measured data and computed results so that an informed decision about their archaeological interpretation can be made. If the only task then remaining is the final labelling of automatically delineated anomalies, interpreters have been freed of some rather mechanistic chores - a most desirable improvement.

For the calculation of 'complex attributes' more than one data set can be used, for example earth resistance and magnetometer data. Such combination, sometimes referred to as 'data fusion', derives new information from the response of archaeological features to different survey techniques and is similar to multi-spectral image classification (see above). For example, if magnetometer data are high and earth resistance measurements low, the causative feature might be a ditch. If, however, the magnetic anomaly is very high and earth resistance is high, it might be a kiln. In this way a classified attribute would help considerably with the archaeological interpretation. A major problem with this approach is the variation in spatial characteristics (Schmidt 2001b) of different geophysical techniques (e.g. peak and trough of magnetic anomalies, see above, and single peaks in earth resistance data). To normalise different anomalies, considerable processing is required and further research in this area is needed (Piro *et al.* 2000).

4. Conclusions

The preceding discussion of relevant technological issues highlighted the contributions from informatics to archaeological prospection. The split into five stages helps to structure the range of applications for a more generic assessment.

Advances in measurements and data recording are very closely intertwined with developments in data capturing and storage. High resolution imaging sensors and 'intelligent' data loggers were only possible after advances in computer memory and miniaturised processing power. Conversely, the challenges posed by the newly developed interferometric radar led to advances in computer science. Acquisition procedures of archaeological prospection methods are often governed by available resources (e.g. light aircrafts) and customary practice. The latter is sometimes simply derived from archaeological field routine (e.g. geophysical surveys on small grids) and computational solutions have to respect these constraints. In this regard they are subordinate to existing practice and operators' preferences. However, advances in information technology can also stimulate changes to current field routine, as shown by the random recording system described by Sauerländer *et al.*

(1999). Only the advances in Delaunay triangulation developed for other applications made measurements without a fixed grid pattern possible. Such major change in geophysical data acquisition would not have been conceivable (or desirable) prior to a shift in the data manipulation framework.

Although information technology had a profound impact on measurements and acquisition procedures, data processing and visualisation are clearly the main applications in archaeological prospection. While the benefits of such procedures are often tremendous, they cannot be a substitute for high quality data in the first place. Data processing only enhances what is already there – and sometimes even introduces undesirable effects (e.g. halos in highpass filtered data). The old adage 'garbage in – garbage out' is a reminder that the imperfections in poorly collected data (e.g. staggering) are often inconsistent and hence resistant to algorithmic remedies. These limitations of 'black box' processing techniques have to be acknowledged, otherwise an over-reliance on the vast number of now available processing tools may lead to poorer data.

Processing and visualisation are crucial intermediaries, helping to unleash the information contained in archaeological prospection data. However, the most important stage is their *archaeological* interpretation. As a result of an integrated prospection strategy one hopes to advance archaeological comprehension or to answer archaeological questions. To this end, the 'hard' data, computationally derived from remote sensing imagery and geophysical surveys, have to be amalgamated with the 'soft' archaeological understanding of landscapes, societies and human behaviour. At this stage the mainly deterministic approaches of information technology clash with the humanities. It has been shown in GIS technology that advances in computing processes allow a departure from strictly deterministic data treatment (e.g. by using perceptions of space rather than 'least cost surfaces' for predictive modelling (Witcher 1999)). Similarly, it may be expected that soft archaeological knowledge will be incorporated into automated interpretation schemes for archaeological prospection data. For the time being, however, human interpreters are essential for the final analysis of data that have been greatly enhanced and simplified through information technology.

One particular example of such computer assistance concerns the use of classification techniques based on several different input parameters (e.g. spectral bands, different geophysical techniques). Combining all data in a multi-layer analysis for their subsequent interpretation is essential. This has always been the approach of human interpreters, comparing maps of different survey results and basing their analysis on a comprehensive understanding of spatial relationships. However, the complexity of emerging patterns rises dramatically with the number of investigated data sets and soon becomes prohibitive for human interpretation. Information technology that automatically simplifies and summarises such hyper-spectral data greatly assists any subsequent interpretation. The use of artificial neural networks may be the best way to expand the remarkable powers of the human brain.

There are a number of prerequisites to achieve any future improvements. First of all, data standards have to be defined so that measurements and processed results can be exchanged more easily between individual researchers and software packages. While not yet overwhelmingly adopted, GeoTIFF has emerged as a useful standard for the exchange of georeferenced remote sensing data. It is supported by several modern software packages and will be a great help when integrating data from different sources. So far there is no accepted standard for the storage of archaeological geophysical data (Schmidt 2002) but a new framework, the Archaeological Grid Format (AGF), is being developed by the author.

In the past, much effort has been spent on the definition of data standards and metadata but the issue of data quality has been neglected. It is crucial for any data integration and analysis that meaningful information on the accuracy and precision of data is available. For example, if geophysical data were collected with a ground accuracy of 0.01m and satellite images, after rectification, are only reliable to within 2m, little can be made of the spatial relationship between these data sets. It is therefore crucial that information on data accuracy is available so that automated analysis can take them into account using geostatistical methods.

The most pressing issue, however, is the access to archaeological prospection data. Geophysical data are not too expensive to commission and many institutions and units now have their own survey equipment. In Britain, the Archaeology Data Service (ADS) has started to archive geophysical data to make them available to interested third parties. With this continuing process it will be possible to use existing surveys for new investigations. The commissioning of aerial photographs is expensive but more importantly, results are often unpredictable and depend on climate, weather history, time of day and a very skilled operator. Fortunately, a large archive of photographs is available for inspections and many archaeological sites have already been recorded, for example in the British National Mapping Programme (Bewley 2001). The most expensive source of data are satellite data. While the price per covered area is often reasonable, the minimum coverage that needs to be bought can make a purchase prohibitively expensive. It is hoped that these data will become more cheaply (or freely?) available and a charging policy that takes the currency of images into account (e.g. half price after 1 year of acquisition) would be highly welcomed.

Overall, the future for further advances in the computer manipulation of archaeological prospection data looks bright and with new data sources, easier access, better computers and novel processing techniques, exciting new results will become possible.

5. Bibliography

Adams, R.E.W. 1980. Swamps, canals and the locations of Ancient Maya cities. *Antiquity* Vol. 54:206-14.

Becker, H. 1995. From Nanotesla to Picotesla – a New Window for Magnetic Prospecting in Archaeology. *Archaeological Prospection* Vol. 2(4): 217-228

Becker, H. 1999. Duo- and Quadro-sensor Configuration for High Speed/High Resolution Magnetic Prospecting with Caesium Magnetometer. In J.W.E. Fassbinder and W.E. Irlinger (eds.) *Archaeological Prospection 1999, Arbeitshefte des Bayerischen Landesamtes für Denkmalpflege*, Munich: Lipp Verlag, pp. 100-105.

Bewley, B. 2001. Understanding England's Historic Landscapes: An Aerial Perspective. *Landscapes*. Vol. 2(1): 74-84.

Blakely R.J. 1996, *Potential Theory in Gravity and Magnetic Applications*. Cambridge: Cambridge University Press

Camerlynck, C., M. Dabas and C. Panissod, 1994. Comparison between GPR and four Electromagnetic Methods for Store Features Characterization: An Example. *Archaeological Prospection.* Vol. 1(1): 5-17.

Cheetham, P. 1996. Visualising Geophysical Data? Getting animated about it. *Computer Applications and Quantitative Methods in Archaeology. CAA96(UK)*. Conference, 17-18 February 1996, York. UK.

Conyers, L.B. and D. Goodman, 1997. *Ground-Penetrating Radar: An Introduction for Archaeologists.* London: AltaMira Press.

Cox, C. 1992. Satellite Imagery, Aerial-Photography and Wetland Archaeology, *World Archaeology* 24(2): 249-267

Dabas, M. 1999. Contribution de la prospection géophysique a large maille et de la géostatistique a l'étude des tracés autoroutiers, *Review d'Archéométrie*, Vol. 23:17-32

David, A. 1995. Geophysical survey in archaeological field evaluation, *English Heritage Research and Professional Services Guideline*, Vol. 1. London: English Heritage.

Dittrich, G. and Koppelt, U. 1997. Quantitative interpretation of magnetic data over settlement structures by inverse modelling, *Archaeological Prospection* Vol. 4(4): 165-177

Doneus, M. 2001. Precision mapping and interpretation of oblique aerial photographs, *Archaeological Prospection* Vol. 8(1): 13-27

Eder-Hinterleitner, A., Neubauer, W. and Melichar, P. 1996. Restoring magnetic anomalies, *Archaeological Prospection* Vol. 3(4): 185-197

Fassbinder, J.W.E. and W.E. Irlinger, 1994. Aerial and Magnetic Prospection of an Eleventh to Thirteenth Century Motte in Bavaria. *Archaeological Prospection* Vol. 1(1): 65-69

Fowler, M. J. F. 1994. Ground Cover Mapping from Multispectral Satellite Imagery. *AARGnews* 9: 11-19

Fowler, M. J. F. 2000. The Colosseum of Rome from 681 kilometres. *AARGnews* 20: 47-50

Gaffney, C., J. Gater and S. Ovenden, 1991. *The Use of Geophysical Techniques in Archaeological Evaluations*. IFA Technical Paper Number 9.

Gimson, H. 2001. *An Assessment of the Variables within Fluxgate Gradiometer Data Collection Processes*. University of Bradford: Unpublished MSc Dissertation

Haigh, J.G.B. 2000. Developing rectification programs for small computers, *Archaeological Prospection* Vol. 7(1): 1-16

Herwanger J., H. Maurer, A.G. Green and J. Leckebusch, 2000. 3-D inversions of magnetic gradiometer data in archeological prospecting: Possibilities and limitations. *Geophysics*. Vol. 65(3): 849-860

Holden, N. 2001. The use of laser scanning and multi spectra imager in environmental mapping. In M. Doneus, A. Eder-Hinterleitner and W. Neubauer (eds.) *Archaeological Prospection 2001*. Vienna: Austrian Academy of Sciences. pp. 114-116

Leckebusch, J. and Peikert, R. 2001. Investigating the true resolution and three-dimensional capabilities of ground-penetrating radar data in archaeological surveys: measurements in a sand box, *Archaeological Prospection* Vol. 8(1): 29-40

Leckebusch, J. 2001. *Die Anwendung des Bodenradars (GPR) in der archäologischen Prospektion: 3D-Visualisierung und Interpretation.* Rahden/Westf.: Verlag Marie Leidorf GmbH.

Li, X. and H.-J. Götze, 1999. Comparison of some gridding methods. *The Leading Edge*. Vol. 18(8): 898-900.

Marshall, A. 1998. *Use of animation to display survey data*. http://www.brad.ac.uk/acad/archsci/field_proj/amarsh/animtext.htm [Last visited 9 February 2003]

McHugh, W.P., J.F. McCauley, C.V. Haynes, C.S. Breed and G.G. Schaber, 1988. Paleorivers and Geoarchaeology in the Southern Egyptian Sahara. *Geoarchaeology: An International Journal* Vol. 3(1): 1-40.

Neubauer, W. and Eder-Hinterleitner, A. 1997. Resistivity and magnetics of the Roman town Carnuntum, Austria: an example of combined interpretation of prospection data, *Archaeological Prospection* Vol. 4(4): 179-189

Neubauer, W. and Eder-Hinterleitner, A. 1997b. 3D-interpretation of postprocessed archaeological magnetic prospection data, *Archaeological Prospection* Vol. 4(4): 191-205

Norton S.J. and A.J. Witten, 1998. Target Parameter Estimation and Survey Design in Magnetometry. *Journal of Environmental and Engineering Geophysics*. Vol. 3: 147-155

Palmer, R. 2000. Using AirPhoto 1.51 *AARGnews* 21: 17-23

Piro, S., Mauriello, P. and Cammarano, F. 2000. Quantitative integration of geophysical methods for archaeological prospection, *Archaeological Prospection* Vol. 7(4): 203-213

Redfern, S., Lyons, G., and Redfern, R. M. 1999. Digital elevation modelling of individual monuments from aerial photographs, *Archaeological Prospection* Vol. 6(4): 211-224

Rees W. G. 1990. *Physical Principles of Remote Sensing*. Cambridge: Cambridge University Press.

Sauerländer, S., Kätker, J., Räkers, E., Rüter, H. and Dresen, L. 1999. Using random walk for on-line magnetic surveys, *European Journal of Environmental and Engineering Geophysics*, Vol. 3(2): 91-102

Schmidt, A. and Marshall, A. 1997. Impact of resolution on the interpretation of archaeological prospection data, In A. Sinclair, E. Slater and J. Gowlett (eds.) *Archaeological Sciences 1995*, Oxford: Oxbow Books, pp. 343-348

Schmidt, A. 2001. Software Review, *Archaeological Prospection* Vol. 8(2): 135-137

Schmidt, A. 2001b. Visualisation of multi-source archaeological geophysics data. in M. Cucarzi and P. Conti (eds.) *Filtering, Optimisation and Modelling of Geophysical Data in Archaeological Prospecting.* Rome: Fondazione Ing. Carlo M. Lerici. pp 141-152

Schmidt, A. (2002) *Geophysical Data in Archaeology: A Guide to Good Practise*, ADS series of Guides to Good Practice. Oxford: Oxbow Books, ISBN 1-900188-71-6

Scollar, I. 1998. AirPhoto - A WinNT/Win95 Program for Geometric Processing of Archaeological Air Photos. *AARGnews* 16: 37-38

Sheen, N.P. 1998. *Automatic Interpretation of Archaeological gradiometer Data, Using a Hybrid Neural Network*. University of Bradford: Unpublished PhD Thesis.

Tsokas, G.N. and Hansen, R.O. 2000. On the use of complex attributes and the inferred source parameter estimates in the exploration of archaeological sites, *Archaeological Prospection* Vol. 7(1): 17-30

Vernon, R. W., McDonnell, J. G. and Schmidt, A. 1999. Medieval Iron and Lead Smelting Works: A Geophysical Comparison, In Pollard A. M. (ed.) *Geoarchaeology: exploration, environments, resources*. Geological Society, London, Special Publications. Vol. 165: 15-34

Witcher, R. E. 1999. GIS and Landscapes of Perception, In M. Gillings, D. Mattingly and J. van Dalen (eds.) Geographical Information Systems and Landscape Archaeology, pp. Oxford: Oxbow Books