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# GEOPHYSICAL SURVEY IN ARCHAEOLOGICAL FIELD EVALUATION

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# Geophysical Survey in Archaeological Field Evaluation

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## Preface to the Second Edition

These guidelines are intended to help archaeologists, particularly curators, consultants and project managers, to better understand and engage with the techniques of geophysical survey, for the best results. It is hoped too that practitioners of geophysical survey will find them helpful and that, altogether, the guidance can contribute to raising the consistency and quality of geophysical survey in archaeological field evaluation.

Geophysical survey in archaeology continues to flourish. As of 2006, it is estimated to be a component of at least 23.4% of all evaluations arising from planning applications (http://csweb.bournemouth.ac.uk/aip/aipintro.htm).

The techniques are also finding an increasing role in the presentation and interpretation of archaeological sites, in contributing to archaeological and forensic research, and in helping to satisfy the demand for media coverage of archaeological subjects.

Geophysical survey has a wider academic and professional forum than was the case several years ago. Since its inauguration in 1995 at Bradford University in the UK there has subsequently been a succession of biennial conferences on Archaeological Prospection, held in Japan, Germany, Austria, Poland, Italy and Slovakia, and attended by an ever more cosmopolitan variety of specialists in geophysics and remote sensing. The Environmental and Industrial Geophysics Group (EIGG) of the Geological Society has similarly hosted a continuing series of biennial one-day meetings devoted to recent research in the subject. The journal *Archaeological Prospection*, initiated in 1994, has gone on to establish itself as the main vehicle for publication of relevant research and case studies; and an International Society for Archaeological Prospection (ISAP) was initiated in 2003 (http://www.archprospection.org). Archaeological geophysics is now a component of undergraduate teaching in at least 12 universities, although the only post-graduate degree courses devoted to the subject are the MSc in Archaeological Prospection at the University of Bradford (http://www.brad.ac.uk/archsci/msc_ap.htm) and the MSc in Archaeological Geophysics recently offered at Orkney College of the University of the Highlands and Islands (http://www.orkney.uhi.ac.uk/courses/archaeology/geophysics-at-orkney-college-uhi).

Despite the increasing familiarity with methods and techniques, and a growing number of practitioners, geophysical survey can be both a very technical subject, as well as a fertile area for continuing innovation, commercial exploitation, and integration with other prospecting disciplines. It is clear from our consultations that in these circumstances there remains a need for independent guidance, which the following document is intended to provide – not only for curators of the archaeological resource, but also for others who need to know about the potential and pitfalls in more detail. Our purpose here is above all dedicated to bettering the consistency and quality of geophysical survey in evaluations, especially those arising from development proposals.

Much of what was presented in the first edition remains valid and will be re-iterated here. There are, however, changes reflecting shifts in thinking and approach that have taken place over the last few years. To take one example, the debate on the efficacy of topsoil magnetic susceptibility as an aid to evaluation, which was very topical in the early 1990s, has moderated now that it is increasingly accepted that detailed magnetometer coverage is preferable, and more feasible, over yet larger areas. More importantly, there have been changes in geophysical instrumentation, technology, methodology and software, all of which are having an impact on the choice and performance of geophysical survey under varying conditions. A particular example is the great improvement in the virtues of ground penetrating radar (GPR), now that software and computing power enable both greater coverage and production of more comprehensible display and interpretation. Another significant development, following the influential example of European practice, is the increasing awareness and availability of alkali-vapour as well as fluxgate magnetometers. Both types of magnetometer, as well as other types of sensor, are now being deployed as arrays on mobile platforms, with considerable potential to raise the versatility and speed of ground coverage.

Other areas of rapidly advancing progress include the further integration of geophysical data within Geographical Information Systems (GIS), which has in turn increased the need for consistency of data geo-referencing and archiving. In parallel, there are a growing number of survey projects that seek to integrate ground-based prospecting methods, together with remote sensing technologies such as lidar, to maximise interpretative and analytical potential.

That said, wetlands, alluviated and urban environments persist as challenges to geophysicists. While not relevant here, but to be the subject of future guidance from English Heritage (forthcoming 2008) it is worth noting that the remote examination of the shoreline and seabed is a growing imperative now that maritime archaeological conservation is in the ascendant.

The first edition of this guidance was published in 1995, and this revision is offered in the hope of maintaining a balanced and independent view on best practice in the context of progress since then. With the benefit of much positive advice, comment and discussion from many colleagues, for whose patience and advice we are very thankful, we hope we have improved the content, and its presentation and clarity. As the document is available on line (http://www.english-heritage.org.uk/upload/pdf/GeophysicsGuidelines.pdf) we expect to make future revisions and updates more immediately and easily in future and would, as ever, welcome comment and advice towards these.

## Contents



# Part I
# Standards for Geophysical Survey

## 1 Introduction

There is currently no formalised standard for the conduct of geophysical survey in archaeological field evaluation. For the purpose of this guidance, however, it is expected that such survey will, as far as is reasonably possible, determine the nature of the detectable archaeological resource within a specified area using appropriate methods and practices[1]. These will satisfy the stated aims of the survey project. Members of the Institute of Field Archaeologists (IFA) will, and other practitioners should, comply with the Code of conduct, *Code of approved practice for the regulation of contractual arrangements in field archaeology*, and other relevant by-laws of that Institution[2].

[1] All relevant fieldwork must conform to the Standard and Guidance set out by the Institute of Field Archaeologists for archaeological field evaluation. (http://www.archaeologists.net/modules/icontent/inPages/docs/codes/fldeval2001.pdf)

[2] The IFA is the professional body for archaeologists in the United Kingdom (www.archaeologists.net). It exists to advance the practice of archaeology and allied disciplines by promoting professional standards and ethics for conserving, managing, understanding and promoting enjoyment of heritage. It has about 2500 members in the UK and abroad.

This basic requirement for geophysical survey in archaeology is fairly straightforward, although much will depend on the definition of what is 'reasonably possible'. To help address this, we initially itemise below some more precise requirements that must be achieved; followed in Parts II–IV by more specific guidance on best practice. Part II (Geophysical Survey and Planning) and Part III (Guide to the Choice of Methods) are aimed at those who commission surveys; Part IV is a more in-depth description and assessment of the main methodologies, for those more concerned with these.

## 2 Guidance

### 2.1 Justification for survey

Prior to fieldwork, the geophysical survey requirements must be integrated within a written statement (the project design, specification, written scheme of investigation, or survey contract). This must include an explicit justification for the choice of survey methodology, while retaining some flexibility should this require modification in the light of particular site conditions at the time of fieldwork. The choice of survey methodology will be appropriately matched both with the archaeological and logistical demands of the project.

## 2.2 Fieldwork

All fieldwork should be conducted under the principle of repeatability; in other words, that, within reason, the data obtained should be capable of independent duplication. Fieldworkers must ensure that every effort is made on site to be courteous and considerate in their dealings with landowners, local residents and organisations, respecting all aspects of the environment. A high level of professionalism is necessary at all times.

Correct observance should be made of any legal constraints on site – for instance, the requirement of a Section 42 Licence for survey over scheduled monuments and other protected places, and the licence now needed for survey on National Trust land (Part II, 7.3).

### *2.2.1 The survey grid*

This is the network of control points used to locate the geophysical survey measurements relative to base mapping and/or absolute position on the Earth's surface, (*see* Part IV, 1.1). Whether physically marked on the ground or measured while surveying using a global positioning system (GPS), these must be located to survey-grade accuracy (±0.1m). The survey grid must be independently re-locatable on the ground by a third party, by measurement to local permanent features, and/or by the use of GPS coordinates. All locational information must be geo-referenced. In certain cases (eg where permanent features are absent), and with appropriate permission, it may be acceptable to emplace permanent survey markers.

Care must be taken to ensure that any survey markers or other equipment are not a hazard to people or animals.

### *2.2.2 Magnetometer survey*

Survey must be conducted with a continuously recording magnetometer of appropriate sensitivity.

Area survey must be the preferred method of ground coverage in all instances where this is practicable.

The maximum acceptable sampling interval for an area survey is 0.25m on traverses a maximum of 1m apart.

Magnetometer scanning, as a method of initially assessing the magnetic response of a site, may be used at the discretion of surveyors who are experienced in its application, for devising (or advising upon) an appropriate evaluation strategy that will use other methods. The technique should not otherwise be included in briefs or specifications.

### *2.2.3 Earth resistance: area survey*

The maximum acceptable sampling interval for area surveys is 1m along traverses separated by a maximum of 1m.

Area surveys, using the twin probe (or twin electrode) probe configuration, are the preferred method of ground coverage. The square array (often employed on cart-based systems) is also acceptable for area surveys. Other methods require special justification.

For twin probe systems the mobile probe spacing should usually be 0.5m; wider separations and/or multiplexed arrays require explanation. The equivalent spacing for a square array would typically be 0.75m.

### *2.2.4 Ground penetrating radar survey*

Generally, this technique will be applied for the detailed investigation of a site by individual profiles and the visualisation of the data as time slices. A maximum traverse spacing of 0.5m is recommended with samples taken at intervals of 0.05m.

Specific site conditions and the aims of the survey may require an alternative sampling methodology to be adopted, but this must be fully justified in any supporting specification documents.

Determination of an appropriate sampling interval, centre frequency of antenna(s) used and sub-surface velocities used for depth estimation from the resulting data must be supported through an appropriate survey design, including field test measurements where appropriate.

### *2.2.5 Magnetic susceptibility survey*

Magnetic susceptibility survey should not take precedence over magnetometer survey where the latter is practicable.

Areas of high topsoil magnetic susceptibility should be complemented by detailed area magnetometer survey. Some areas of low or indifferent magnetic susceptibility values should also be sampled with detailed magnetometer coverage, to confirm that under the prevailing site conditions, changes in magnetic susceptibility do correlate with archaeological potential.

The chosen method(s) of magnetic susceptibility measurement must be appropriate to prevailing ground surface conditions.

Measurements of topsoil magnetic susceptibility, for area surveys and transects, must be made at intervals not exceeding 10m. Where possible, such topsoil measurements must be compared and contrasted with those obtained from subsoil and local archaeological features.

## 2.3 Data treatment

Area surveys must be conducted, and subsequent data treated, so as to result in a data-set that is as uniform as possible. Edge-effects between contiguous survey areas should be minimised.

A copy of unprocessed raw data must be retained and archived (*see below*, 6 Archiving).

Raw data collected in the field must be of high quality. Any data-collection artefacts subsequently apparent in the survey data should be identified and removed using appropriate data processing (Part IV, 2.1). All such processing should be clearly described. Any data collection artefacts that cannot be corrected by data processing should be described and clearly distinguished from possible archaeological anomalies.
If data has been seriously compromised during collection, a return to the site to re-survey the affected area(s) should be considered.

## 2.4 Data interpretation

The interpretation of survey data must be undertaken by a competent archaeological geophysicist who is knowledgeable of the archaeological and geomorphological conditions prevailing on site. Consultation must also take place with other site specialists (eg landscape archaeologists, aerial photographers) wherever possible.

The interpretation of magnetometer and magnetic susceptibility data must endeavour to distinguish anthropogenic from other causes of magnetic enhancement on the site(s) concerned.

A clear distinction must always be made between interpretation that is scientifically demonstrable, and interpretation based on informed speculation.

Any reference to 'negative evidence' must be fully qualified and explained. Lack of geophysical anomalies cannot be taken to imply a lack of archaeological features, and in such cases an alternative evaluation procedure – eg trial trenching, or the use of a different geophysical technique – should be considered.

## 2.5 The survey report

All fieldwork must be followed by a report. This will be a clear and succinct text, supported by tables, figures, appendices and references as necessary (*see below*, 2.5.1). It ought to stand independent of supporting material and should combine the qualities of concise technical description linked to lucid and objective analysis and interpretation. It must in the most part be intelligible to specialists and non-specialists alike. It should usually be accompanied by a statement of the authors' and contractors' professional qualifications.

#### *2.5.1 Report structure and contents*

The report will normally contain the following elements:

- title page
- summary or abstract
- introduction
- methods statement
- results
- conclusions
- acknowledgements
- statement of indemnity
- references
- appendices

Further detail on report content is provided in Part II, 4.

#### *2.5.2 Data presentation – plots and plans*

Depending on the geophysical methods used, each report must include:

- a survey location plan demonstrating relationships to other mapped features (minimum scale 1:2500);
- an image of minimally processed survey data (*see* Part IV, 2.2 and 2.3, preferred minimum scale 1:1000);
- where appropriate (*see* Part IV, 2.2) a trace (or X–Y) plot of raw magnetic data (for very large sites, a sample of data might be supplied instead, to support the specific interpretation of anomalies identified from greyscale images);
- specimen profiles, in the case of GPR surveys;
- a greyscale plot, or dot density plot (minimum scale 1:1000);
- and one or more interpretative plans/diagrams (minimum scale 1:1000).

The location plan must be directly relatable to the OS National Grid. Reproduction of any part of an OS map requires copyright permission – see http://www.ordnancesurvey.co.uk/oswebsite/business/copyright/index.html. Each plan and/or plot must have a bar scale (or annotated metric grid) and an accurately oriented north arrow.

Greyscale, dot density and trace (X–Y) plots must also have annotated scales indicating the range of the variables depicted.

GPR profiles require a horizontal scale, and a scale of two-way travel time on the Y-axis. If an estimated depth scale is also included, there must be an explanation in the caption or text as to the supporting analysis. If the ground level is significantly uneven (> ±0.5m) along the survey traverse concerned, a topographically corrected section should also be considered. Each plot must include a key describing the symbols and conventions used.

### 2.6 Dissemination

A copy of the survey report (paper or digital, as required) should be lodged with the Local Authority Historic Environment Record (HER), normally within six months of the completion of fieldwork, but if, necessary, may be delayed until after completion of the full project (*see* Part II, 5.2). This should be a responsibility of the commissioning body, in consultation with the project director and the contractor.

Copies of any report resulting from a survey for which a Section 42 Licence (*see* Part II, 7.3) has been obtained must be sent both to the English Heritage Regional Inspector of Ancient Monuments and to the English Heritage Geophysics Team, Fort Cumberland, Eastney, Portsmouth PO4 9LD.

Details of the survey must be entered on OASIS (*see* Part II, 5.2).

### 2.7 Data archiving

A minimum requirement is that a viable digital copy of the raw survey data must be retained for future interrogation, together with adequate information on the location of the survey and the survey methodology. In addition to storage on a secure medium, appropriate documentation of survey practice and data files is also required. The archiving of data associated with geophysical survey should follow the advice provided in *Geophysical Data in Archaeology: A Guide to Good Practice* (Schmidt 2002), together with the advice in *Archaeological Archives: A Guide to Best Practice in Creation, Compilation, Transfer and Curation* (Brown 2007).

### 2.8 Competence of survey personnel

All staff, including sub-contractors, must be suitably qualified and competent for their project roles, employed in line with relevant legislation and IFA by-laws (where relevant). The project manager must have:

- competence in basic metric survey procedure;
- experience in a supervised capacity of at least 30 different site surveys, or a minimum of three full years' supervised experience of archaeological geophysics;
- and a degree in archaeology and/or an appropriate science (eg MSc in Archaeological Prospection).

Membership of professional institutions or relevant associations, while not a requirement, should also be a consideration – and is encouraged. These include:

Institute of Field Archaeologists (IFA)
European Association of Geoscientists & Engineers (EAGE)
European GPR Association (EuroGPR)

Less experienced staff must be supervised throughout any fieldwork, subsequent data treatment, interpretation of the data and/or report preparation.

# Part II
# Geophysical Survey and Planning

## 1 Archaeology and planning

Government guidance (DoE 1990) states that 'where nationally important archaeological remains, whether scheduled or not, are affected by proposed development there should be a presumption in favour of their physical preservation'. From this stems the necessity for field evaluation as a preliminary stage in the planning process. The potential contribution of geophysical survey should be considered in each instance where development is proposed.

As geophysical survey will often be a crucial element in site evaluation it is most important that it should be correctly integrated within briefs and specifications and within subsequent project management.

## 2 MoRPHE

Field evaluation, and any geophysical survey that it includes, should be part of an integrated programme of research. Management of Research Projects in the Historic Environment (MoRPHE) is a system developed to promote this process. A typical project will often proceed through a number of stages (Lee 2006) and the role of geophysical survey is described broadly in relation to these. Detailed discussion of individual aspects of survey procedure follows in the subsequent sections.

### 2.1 Start-up and planning

Consideration of geophysical survey can be most crucial during the early stages of project planning. Indeed, in many programmes of archaeological evaluation the geophysical survey will be completed and acted upon, as a self-contained project, entirely within this phase. In the right circumstances such survey can provide information of great clarity on the extent and nature of archaeological deposits and features. Even in less perfect conditions, survey results can be highly informative, and therefore it is important that geophysical methods should always be considered at the outset of each programme of evaluation.

Most evaluations will be initiated with a desktop study, often starting with an interrogation of the relevant Historic Environment Record (HER), followed by an assessment of all other extant documentary records, including aerial photographic (AP) coverage (ACAO 1993). Such a study should also determine the following information relevant to geophysical survey:

- solid geology
- drift geology
- soil type
- current land use and surface conditions
- history of previous ground disturbance
- history of previous geophysical survey (if any)
- legal status of the site

Once this information is available, the potential for geophysical survey should be assessed. If geophysical survey is then agreed to be relevant, a project design or specification can be drawn up, calling upon expert advice in order to avoid wasteful or misdirected outlay of resources, or missed opportunities.

### 2.2 Execution

Project Execution, as defined here, includes fieldwork, assessment of potential, archive deposition, and dissemination (Lee 2006).

#### 2.2.1 Fieldwork

The following stages of geophysical survey fieldwork should be considered and planned for, where appropriate:

(a) Pilot (test or trial) survey: it may occasionally be necessary for a preliminary assessment to be made of a site's response to geophysical survey, particularly where large areas (>20ha) are concerned. This procedure should indicate whether local conditions are suitable for useful results to be obtained and what techniques and sampling methodology may be most appropriate. Such preliminary information, based on expert assessment, can forestall the wasteful deployment of resources on inappropriate techniques and on sites where the use of geophysics is unlikely to be helpful. A brief site visit may be all that is required. Any pilot survey should not usually take more than a day to achieve, and the results should be made available immediately for incorporation into the project design. Project managers should ensure that they are made aware of the geophysical potential, or lack of it, of their site(s) at the outset; the justification for survey must be clear.

(b) Full survey: once this justification is assured an agreed survey strategy can proceed. This may be full or partial coverage of the site at high or low levels of detail, using one or more techniques, depending on the strategy adopted.

(c) Extended coverage: in some circumstances it may be necessary to accommodate additional survey if earlier results (or subsequent excavation) indicate that this would be profitable. Where appropriate, allowance for such contingencies should be made in briefs and specifications.

It is particularly important at this time to establish a secure and agreed timetable in which the above stages of survey are correctly integrated with the other evaluation strategies. In many instances it will be for survey to take place after field walking, utilising a shared grid system, but before trial trenching or excavation. The timetable should be sufficiently flexible to accommodate additional contingency survey, and costing should allow for this. Above all, the timetable should permit adequate time for the results of geophysical survey to be fully reported in order to inform subsequent project planning.

Once the report has been made available, allowance should be made for the project team to communicate with the surveyors to discuss any outstanding matters, especially as these may relate to the archaeological interpretation of the geophysical data.

Good timetabling must be linked with full and informed cooperation between all parties. Particularly relevant to geophysical survey is that landowners and/or their agents and/or tenants have been informed and given their permissions for the survey to take place. Obtaining such permissions, as well as details of access and the resolving of any other local complications, should usually be the responsibility of the project manager rather than that of the surveyors.

The above recommendations should be followed wherever possible. It is acknowledged, however, that very often practical necessity – particularly shortage of time – may dictate a different course of action. For instance, there may be insufficient time to prepare a full report in advance of excavation or of the development itself, in which case survey plots produced in the field must be acted upon directly.

Once the survey strategy has been agreed, costed, timetabled and the relevant permissions obtained, the fieldwork can go ahead accordingly. Actual fieldwork procedures are discussed more fully below in Part IV.

In the context of the full research programme, geophysical survey will usually be incorporated in the Initiation Stage, allowing its results to direct the subsequent Execution Stage of the larger programme.

#### *2.2.2 Assessment of potential*

There are two sets of instances where assessment of the potential of the geophysical survey data may be required as part of the Execution Stage of the larger programme:

(a) where such data indicates that further survey would be of significant advantage to the realisation of specified archaeological research objectives. There are many instances where extended geophysical survey could significantly enhance the value of a project by placing a partially recorded site or sites within a wider spatial context, in which crucial relationships with other features, sites or the wider landscape can be better understood. This synthetic role of geophysical survey should never be underestimated.

Any such additional survey should be justified and planned for in an updated project design. It should, if possible, employ the original team; if other surveyors must be used then the project manager should ensure that full continuity and integration of survey procedure and interpretation is achieved. If possible, the original raw field data should be made accessible to the incoming surveyors (*see below*, 2.2.3).

(b) where the geophysical survey data, in its own right, has significant potential for advancing research into geophysical prospecting techniques, or the interpretation of geophysical data. This potential should always be assessed at the outset of a project, and kept under review.

In both senses (a) and (b) above, geophysical survey data has a research potential and should be considered alongside other more customary 'post excavation' data. If deemed significant by the project team, any scope for realisation of this potential should be included in an updated project design. The latter will include provision for the publication of results either within the main project report, or as a separate paper in a more specialised publication.

#### *2.2.3 Archive deposition*

While the full details of the geophysical survey will be archived at the conclusion of the survey project (*see below*, 6 Archiving), the project manager and survey staff should be aware of the necessity of recording and safeguarding raw data, the data processing steps undertaken, and locational information, at all appropriate stages during the course of the project.

#### *2.2.4 Dissemination*

The results of the main research programme will be drawn up, in draft report form, for review and subsequent publication. However, the report on the geophysical survey will usually have been completed and presented to the project team and/or commissioning body earlier. Close liaison with the project team must continue, however, to ensure that the geophysical data and its interpretation is presented in appropriate proportion to its contribution to the stated objectives of the wider programme.

The following options can be considered for the final presentation of the geophysical survey results:

(a) that a summary should be included in the main report text, while the survey report and related data is retained in archive;

(b) that a summary should be included in the main report text, while the survey report is included as an appendix;

(c) that the survey report should be modified for reproduction in the main report text.

It is not acceptable for the contribution of geophysical survey to be ignored, even if results have been indifferent or negative. A minimum requirement is that a summary statement is recorded in the overall programme report.

It should be noted that under the Copyright, Designs and Patents Act 1988 the organisation or person undertaking field and reporting work retains the copyright to the material, unless stated otherwise in the contract for the work. This position should be made clear to all relevant parties at the outset of work (IFA 2001, Appendix 5).

Every effort should be made to ensure that the survey report becomes publicly accessible. All field data and reports will be deposited with the site archive, and the HER updated. Where results for some reason cannot be disclosed, a minimal record should be made and fully updated within a reasonable time (normally six months). A fuller discussion of dissemination and archiving follows in sections 5 and 6 below.

### 2.3 Closure

Once the survey project has been concluded, time should be planned for documentation of any follow-on actions, unresolved issues and lessons learned.

## 3 Briefs and specifications

Definitions of these terms are provided in the glossary and references can be found in the bibliography. In particular, readers are referred to the 'Standard and Guidance for Archaeological Field Evaluation' published by the Institute of Field Archaeologists (IFA 2001: http://www.archaeologists.net/modules/icontent/index.php?page=15).

In a commercial tendering situation, briefs are provided by the client, and tenders invited (Project Start Up: *see above*); tenderers will respond with a specification or project design (Project Initiation: *see above*). If a tenderer feels that a differing approach to that identified in the brief might better suit the circumstances, then this can be proposed as an alternative and separately costed specification. The final specification or project design will then be agreed with the planning archaeologist or curator, and will form part of a contract that must be drawn up in writing. Being of such a specialist nature, geophysical survey is often sub contracted; in either case particular care is required, and advice on this can be acquired from various sources (eg CBA 1982; Darvill 1993; Darvill and Atkins 1991; IFA 2001).

While the difficulties of working within a developer-funded scenario are not underestimated, it is not acceptable for geophysical survey to be commissioned on the hoof, after a hasty phone call.

The following sections on briefs and specifications are a guide only, pointing to the type and level of information usually required. These are not meant to be inflexible, and the documentation will need to be adapted to the circumstances of each survey or project.

### 3.1 The brief

A requirement for geophysical survey may become apparent during either the appraisal or the assessment stage in the response to an application for development. The earlier this is realised and incorporated into a brief the better. Clients and curators are encouraged to seek specialist advice to ensure that the content of the brief is fully appropriate to the circumstances in each case. If necessary, independent advice on geophysical survey can be sought from outside the commercial sector, for instance from the English Heritage Regional Science Advisors or from the English Heritage Geophysics Team (*see* contact details in Appendix II).

The following information usually needs to be provided in a brief:

*Summary:* a concise statement (200 words maximum) of the purpose of the survey, what type of survey is required, by whom, why, where and by when a report must be delivered.

*Background:* a brief account of the relevant context to the survey requirement. It must include the following:

- OS NGR location(s)
- designations (eg Scheduled Monument number(s))
- archaeological context (eg evidence from APs, surface remains, documents)
- relevant recent history of the site (eg landscaping)
- reason for the survey
- any wider project context

*Site conditions:* a site description, to include the following:

- underlying solid and drift geology, and soil type(s)

- ground/vegetation conditions at the time of the survey
- ownership

*Survey location:* a map of a suitable scale to show the context, location and size of the proposed survey area(s).

*The geophysical survey requirement:* this will state the objectives of the geophysical survey and the methodology by which these are intended to be achieved. The detail of the required methodology will be provided in a separate specification (which may follow as part of a combined Brief and Specification). In the meantime it is sufficient to identify that geophysical survey is required, although a more specific methodology can be indicated, for example:

- earth resistance area survey
- detailed magnetometer area survey
- detailed GPR area survey
- GPR profiles

*Timetable:* a statement or tabulation of the project timetable, emphasising the scheduling of fieldwork and report presentation.

*Further information:* anything further of broad relevance to enabling the survey work.

### 3.2 The Specification

More specific and detailed survey requirements are described in The Specification. This will usually be separate from the preceding brief, but if circumstances permit, the two may be combined as part of the same document.

The specification should include the following:

*Summary:* a resumé of the information provided by the brief.

*Survey location:* an annotated map or plan indicating which areas are to be surveyed. If different areas require differing survey methodologies, then these should be indicated if possible. The map can also be used to provide other important information (eg access routes) where necessary.

*The survey grid/co-ordinate system:* the following needs to be identified:

- a temporary/permanent survey grid is to be established
- responsibility for doing so (usually the survey team)
- accurate location of grid intersections (±0.1m)
- georeferencing (measurements to permanent features to allow the grid to be exactly re-located if necessary by a third party)

*Survey type:* a statement of the geophysical technique to be used – examples might be:

- fluxgate gradiometer area survey
- alkali-vapour magnetometer area survey
- earth resistance area survey
- EM soil conductivity area survey
- GPR profiling
- GPR area survey

*Survey instrumentation:* it is not usually necessary to specify the make or model of equipment (however, these should be stated in the resulting survey report).

GPR equipment must be suitable to meet the required specification, specifically any requirements for the centre frequency of the antenna(s) to be used and the necessity for antenna shielding. Note that, should topographic correction be a requirement of this or any other type of survey, care must be taken that this is accounted for and costed as appropriate.

*Survey methodology:* a statement of methodology. For example: all methodologies will follow those recommended in the appropriate operators' manuals for:

- traverse/line separation
- probe configuration (earth resistance surveys)
- mobile probe spacing (earth resistance surveys)

*Sampling interval/density:* the sampling regime must be stated. The examples listed in Table 1 are suggested as the widest acceptable intervals and traverse separations for evaluations (although circumstances may dictate a denser sampling for more detailed characterisations).

*The report:* a statement to the effect that all fieldwork, data processing and reporting must follow the recommendations set out in these guidelines. State how many copies of the report are required, and what arrangements are in place to deposit one of these with the HER.

*Digital archiving:* a statement of what arrangements are in place to ensure that both survey documentation and digital data are archived in line with current guidance (*see* 6 Archiving).

*Access:* a statement of access arrangements, providing clarity on how access to the site is to be achieved, and any conditions on this, together with a statement of whose responsibility it is to obtain permission from the landowner and/or manager.

*Legal and other provisions:* a statement of any legal or other limitations relevant to the survey (eg over Scheduled Monuments or on National Trust property), and a clear statement of whose responsibility it is to acquire the relevant consents and licences in such cases, and when this is to be done.

*Timetable:* a statement of time constraints (eg for access to site), and the date by when the report must be delivered.

*Feedback:* a statement that the results of any trial trenching or other excavation will be made known to the geophysical survey contractor, and that any subsequent commentary by the contractor, will be included in the final project report, if appropriate.

**Table 1** Recommended sampling densities for various geophysical survey techniques.

| *Technique* | *Evaluation (reading × traverse)* | *Characterisation (reading × traverse)* | *For further information see* |
|---|---|---|---|
| magnetometer | 0.25m × 1.0m | 0.25m × 0.5m | Part IV, 1.2 |
| earth resistance | 1m × 1m | 0.5m × 1m or 0.5m × 0.5m | Part IV, 1.3 |
| GPR* | 0.05m × 1m | 0.05m × 0.5m | Part IV, 1.4 |
| electromagnetic (EM) | 1m × 1m | 0.5m × 1m or 0.5m × 0.5m | Part IV, 1.5 |
| EM for geomorphology | 5m × 5m | – | Part IV, 1.5 |
| topsoil magnetic susceptibility | 10m × 10m | – | Part IV, 1.6 |

* These are general recommendations but for GPR survey appropriate reading intervals are highly dependent on the centre frequency of the antenna used.

*Further information:* anything further of specific relevance to realising the objectives of the geophysical survey.

Note that any pilot survey should be the subject of separate and equivalently detailed documentation, although this may be undertaken in advance to inform the completion of a final specification.

## 4 The survey report

The end product of any geophysical survey is the survey report. This should be a clear and succinct text supported by tables, figures, appendices and references as necessary. It should stand independently of supporting material and should combine the qualities of concise technical description linked to lucid and objective analysis and interpretation. It should be intelligible to specialists and non specialists alike. It should usually be accompanied by a statement of the authors' and contractors' professional qualifications.

The minimum requirements of such a report are summarised in the listing below, parts of which are then described in further detail.

**Title page:** title of report
author(s)
contractor
client
report reference number
date

**Summary of results:** an 'abstract'

**Introduction:** site location (including NGR)
site description/history
survey objectives

**Methods:** survey methods used
reasons for this choice
date(s) of fieldwork
grid location
geophysical instruments used
sampling intervals
equipment configurations
method(s) of data capture
method(s) of data processing
variables used for the above
method(s) of data presentation

**Results:** description
interpretation

**Conclusions:** assessment of achievement (or not) of survey objectives
results summarised
implications
geophysical research value
recommendations (if appropriate)

**Statement of indemnity**

**Acknowledgements**

**References:** list of works referred to

**Appendices:** technical details of methodology and instrumentation, data (eg mag susc tables; grid location measurements)

**Plans/plots:** survey grid location (1:2500 min)
plot(s) of raw data (1:1000 min)
minimally enhanced
X–Y traces of magnetic data, where appropriate
plot(s) of enhanced data (1:1000 min)
grey tone (or dot density)
interpretation diagram (1:1000 min)

### 4.1 Summary

This should be a *précis* of the principal objectives of the survey and the extent to which they were achieved.

### 4.2 Introduction

This should provide the reasons for the survey, set against a brief description of the site(s) or area(s) concerned. It should include reference to solid and drift geology, soil type and local geomorphology. The archaeological background (if known) should be summarised and reference made to previous fieldwork and/or publications, as well as to other relevant information (eg from the aerial photographic record and/or any related field investigations).

Other introductory items include: date(s) of fieldwork, National Grid References, any research objectives, legal status of site(s), ground conditions, weather, site peculiarities, documentary history, and any other relevant information.

### 4.3 Methods

The methods statement should be a concise account of the survey methods used, referring to an appendix or to other appropriate source for a more detailed description of standard methodologies. Above all, it is important that the instrument type is specified, how the data was gathered and at what sampling interval. This information should be followed by noting the methods of data processing and software used. Reference should be made to the plots presented with the report, explaining reasons for their choice, if necessary.

### 4.4 Results

This section is usually the most variable in content between one survey and another, and between different practitioners' descriptions and analyses of their respective results. Where more than one survey technique has been used it is usually best to describe each set of results and their interpretation under a separate subsection. Similarly, where non contiguous subdivisions of the survey area are involved, these should each be dealt with in turn.

Much will depend on the clarity and simplicity or – by contrast – the complexity, of the results as to how the report should proceed. Some authors may prefer to write a factual account of the survey results, followed by a section on their interpretation and discussion. An alternative is to set out a blend of objective description and explanatory interpretation that draws upon supporting information from other sources (eg augering, aerial photography, trial trenching, etc). However, exhaustive narrative detail, anomaly by anomaly, is tedious and should be avoided; instead, the maximum use should be made of accompanying plots and interpretation diagram(s). Where plots and diagrams are mostly self explanatory, the associated text should be brief. Most importantly, explanations must be clearly expressed and the division between objective reasoning and more subjective circumstantial inference made distinct. The interpretation of archaeological geophysical data must inevitably include surmise – and this should be encouraged – but the reader must be left in no doubt precisely where the areas of uncertainty lie.

### 4.5 Conclusions

The conclusions should address the survey results with reference to the original objectives. The overall archaeological significance of the survey findings can be summarised and conclusions drawn, where necessary, about the need for future survey or research. In developer-funded evaluations, unless it is specifically requested in the specification, it is not appropriate for the contractor to launch into discursive assessments of archaeological importance or to make curatorial recommendations.

The names and affiliations of the author(s) of the report should be stated at its conclusion, as well as the date of its final draft (or this information could be supplied at the beginning of the report).

### 4.6 Site location plan(s)

In most cases these should be based on a large-scale OS map, displaying National Grid eastings and northings, and for which copyright permission must be obtained. Other base plans may be acceptable, so long as they allow the entire survey grid to be shown, and they include features that can be clearly and accurately re-located on the ground, or identified on the appropriate OS map.

The survey grid should be superimposed on such a base map, and the opportunity may be taken to number the grid squares for ease of reference from the text; or the survey areas may be shown by outline only. In either case it is necessary to ensure that the surveyed area is unambiguously indicated on the location plan. Areas of the grid covered by different techniques can be indicated by differential shading or colours. Grid location measurements can be included on the plan, so long as clarity is preserved, or can be tabulated in an appendix (although it is acceptable for this information to be retained only on archive plans or in site notes).

### 4.7 Data presentation – plots and plans:

Much as one may hope that readers will have assimilated all the written detail of the report it is probably true that the greatest attention is paid to the summary and conclusions, and especially to the accompanying plots and interpretation diagram(s). These latter, then, should be of a very high standard and should include the following components (sections 4.8, 4.9 and 4.10 below).

### 4.8 Plots of raw data

Each survey report should include at least one plot of minimally processed, raw data. Raw magnetometer data is usually best displayed in greyscale or X–Y trace format (but not as 'wire-frame' diagrams) although this may not be practical for very large surveys. Raw earth resistance data is better plotted in greyscale or dot density format. Raw data may undergo minimal processing (eg edge-matching, zigzag correction), but should not be filtered. There should be a statement of any processing that has been applied.

### 4.9 Plots of processed data

Although many experimental attempts may be made to enhance images of the geophysical data from a site, only the most representative of these need be included in the report. It may be necessary to state in the text that this is so, and that the interpretation provided is a synthesis.

Each plot should be annotated with the details of the type of enhancement used. All plots, whether of raw or processed data, should include scale bars, scales indicating the range and magnitude of the data on display, north arrows and grid coordinates (where necessary). As far as possible, separate plots should be at the same scale and orientation to enable direct comparison. A scale of 1:500 is often suitable, although scales as small as 1:1 000 are acceptable for large surveys. Plots may need to be at a scale sufficiently large to allow measurements to be made from them for the subsequent location of excavation trenches. Greyscale plots are to be favoured for the display of magnetometer data but should be accompanied by trace plots where these provide complementary information that has influenced the interpretation cited (*see* Part IV, 2.2.1). Dot density plots, contour plots, 3D 'wire-frame' plots and the like can be used additionally, where helpful. The usefulness of colours for data images lacks the subtlety of greyscale and so need only be used sparingly, if at all (but colour is of course otherwise highly advantageous in other plans and diagrams). The above recommendations are for plots of detailed area survey by magnetometer or earth resistance meter. Rather different presentations may be required for other classes of data. Closely spaced magnetic susceptibility, phosphate or other point data may be presented similarly, although symbols of proportional size, or of graded shading, are more effective for more widely spaced survey data. A Key should always be provided. Profile data (pseudo-sections, GPR, etc) can be presented in tonal plots or in colour scales.

### 4.10 Interpretative diagrams

In some cases the survey plots by themselves are of such stark clarity that further interpretative aid, beyond annotation, and description in the report text, is unnecessary. However, it is usually essential to include a diagram, or diagrams, as a supplement to the interpretation provided in the text. It is recommended that such graphics are at the same scale as the survey plot(s), for ease of direct comparison, or can be provided at a smaller scale as an overview of the wider picture. In some instances, the plots themselves may be annotated, but this can be visually confusing and should therefore always be accompanied by an unannotated plot for comparison.

The creation of interpretative diagrams is not an exact science, and often involves the translation of a synthesis of various lines of evidence into a single graphic image. While such a diagram will convey much that is objectively true of the original data, it will also, to some extent, convey more subjective impressions. As stipulated above concerning data interpretation (4.4 Results), it is crucial that the distinction between fact and surmise is clear. To achieve this it is acceptable to provide two diagrams: one that shows an objective simplification of all the geophysical data, and another one that shows a more subjective archaeological interpretation of the first. For the second diagram, particularly if it is the only interpretative diagram to be used, it is important that the graphical conventions convey the nuances of the interpretation, but are not misleading where there is ambiguity or uncertainty. For instance, bold lines and sharp edges should be avoided when attempting to delineate the oft quoted 'tentative' anomalies/features. The use of too many conventions and/or colours can be extremely confusing and should be avoided. A full, explanatory key of any conventions, symbols, and colours and shadings used is essential.

## 5 Dissemination

### 5.1 Sources of information

Information about geophysical surveys undertaken in England can be obtained from the following sources.

*English Heritage Geophysical Survey Database* (http://sdb2.eng-h.gov.uk) This is an on-line index of geophysical surveys undertaken by English Heritage since 1972, with hypertext links to many reports completed since 1993. The database also includes information about all surveys undertaken on scheduled sites as a consequence of Section 42 consents (*see below*, sections 7.2 and 7.3). A limited number of commercial surveys are also included.

*Archaeological Investigations Project (AIP)* This includes data from archaeological investigations in England from 1990, with the resulting gazetteers available online. The entries, which include a separate category devoted to geophysical survey, comprise short abstracts summarising the work carried out, information about the location of the site and investigating authority/body and bibliographic references. (http://csweb.bournemouth.ac.uk/aip/aipintro.htm)

Gazetteers that include some information on geophysical surveys are also being developed in Ireland (excavations.ie), Wales (CBA Wales) and Scotland (Council for Scottish Archaeology).

*National Monuments Record Excavation Index*, based in the NMR offices in Swindon, is in partnership with the AIP, and its online catalogue has a limited number of summaries of geophysical surveys (3418 records, April 2008).

*Archaeological Data Service (ADS)* The ArchSearch facility is the online catalogue of the ADS http://ads.ahds.ac.uk/catalogue/ and allows the searching of records provided by the AIP, NMR Excavation Index, and the OASIS project (*see below*, section 5.2), as well as the databases of many other participating projects and organisations. It is therefore possible to use the facility to search for geophysical survey information, where each survey is described in a summarised form. A small number (13) of survey reports from West Yorkshire can be accessed in their entirety, together with the geophysical data (http://ads.ahds.ac.uk/catalogue/projArch/wyas/).

*Historic Environment Records (HERs) and Sites and Monuments Records (SMRs)* These records, increasingly known as HERs, are maintained by each local authority (LA) and constitute each area's fundamental stock-take of historic environment information (http://www.algao.org.uk/la_arch/fs_HERs.htm).

Most HERs include information about geophysical surveys, which is currently abstracted by the AIP and hence made available in the AIP gazetteers, and through the NMR, and ArchSearch. Most HERs also hold copies of geophysical survey reports for the LA area concerned, but with varying consistency, coverage and formats.

*Other published sources* The sources described above are aimed particularly at accessing information from the mass of so-called grey literature. Additional information about specific surveys or projects can of course be found throughout much of the published domain (see, for example, references and the list of websites below). The leading journal for the publication of research and case studies is *Archaeological Prospection* (http://www3.interscience.wiley.com). A combined catalogue of many libraries' holdings is accessible at http://ads.ahds.ac.uk/catalogue/ARCHway.html.

*International Society for Archaeological Prospection (ISAP)* This society was established in 2003 and is the main forum for communication within the discipline, including an email discussion group and a regular electronic newsletter. All practitioners are advised to join (http://www.bradford.ac.uk/acad/archsci/archprospection/).

### 5.2 Dissemination requirements

Geophysical surveyors, and their clients, face a responsibility to ensure:

- that a copy of the full survey report is deposited with the relevant HER (preferably within 6 months of completion);
- and that reports on surveys over Scheduled Monuments are submitted to English Heritage (within 3 months of the completion of the work: *see below*, section 7.3).

These obligations will ensure that fundamental information on surveys is made available for consultation, and allow for the continued public accessibility of summary information through the sources and mechanisms listed above.

It is recognised that public dissemination may at times not be appropriate (eg in the case of sites vulnerable to looting, or where sensitive planning issues are at stake), but the principle remains that, excepting such circumstances, survey information should be made as widely accessible as possible. Client confidentiality can be respected for reports associated with a planning application, but these should be submitted to the HER within a reasonable time (preferably within six months of the notification of results to the LA).

Summary information on geophysical survey is now gathered at source as part of the OASIS project (Online AccesS to the Index of archaeological investigationS: http://ads.ahds.ac.uk/project/oasis/). It is therefore a third responsibility for surveyors and/or their clients to complete the on-line OASIS sub-form.

It should be further incumbent on the geophysical surveying community not only to make available information on specific surveys, but more widely to continue to raise the profile of its research and results through education and outreach, using all available media.

## 6 Archiving

This subject is dealt with comprehensively in the Archaeology Data Service document *Geophysical Data in Archaeology: a Guide to Good Practice* (Schmidt 2002). All those involved in the acquisition and deposition of geophysical information should be familiar with this guidance and implement it where practicable as current good practice.

At present there is a minimum requirement that a report (*see above*, section 5.2) on each geophysical survey should be deposited with the local HER.

The ADS Guide (Schmidt 2002) proposes that, in addition and as a foundation for adequate digital archiving, there should be a systematic and consistent tabulation of information about the survey. At present this is not widely practised. However, current proposals are seeking, through the development of the OASIS project, to provide a single tabulation that subsumes the various current database requirements into a single accessible source of information about geophysical surveys. Until further guidance on this becomes available the survey report represents the minimum requirement.

All geophysical data are now digital and the preservation of these as a viable future resource is a major consideration for all concerned. It is crucial that the generators of such data should have a strategy in place, from the outset of a project, that allows for their adequate storage, security and long-term accessibility (Schmidt 2002, section 4). At present, requirements for digital archiving may be imposed through the commissioning or specification process where conformity with a particular digital archiving policy or agency is a requirement. Surveyors should always make sure that a consultation has taken place at the start of a project to ensure that appropriate procedures for depositing archives are incorporated in the specification or project design.

The only national and international facility for digital data deposition is provided by the Archaeology Data Service (ADS: http://ads.ahds.ac.uk/project/collpol.html) and all those concerned should make themselves aware of its current policy and requirements, and seek advice as necessary.

In conclusion, until further guidance becomes available, the minimum requirements related to the archiving of digital geophysical data are that:

- each project has a responsible digital archiving strategy, agreed between contractor, client and repository;
- this allows for the adequate storage, security and long-term accessibility of both raw and 'improved' geophysical data (*sensu* Schmidt 2002);
- the survey report includes all relevant survey and data documentation, preferably tabulated for ease of future reference; and
- ADS advice and good practice is sought and followed.

## 7 Legal considerations

Note: it is intended that new heritage protection legislation, currently expressed in the Draft Heritage Protection Bill, published as we go to press (April 2008), will come into effect from about 2010. Once enacted, this new Bill will supersede previous relevant legislation such as the Ancient Monuments & Archaeological Areas Act 1979. The advice that follows reflects the current situation, but will be updated once the new legislation is confirmed. For the moment, we anticipate that the licensing requirements referred to below (7.2, 7.3) will be retained for England, for 'registered heritage structures' (including former Scheduled Sites), and may be extended to include registered 'heritage open spaces' (registered parks, gardens and battlefields). The draft Bill may be accessed at: http://www.culture.gov.uk/Reference_library/Publications/archive_2008/DraftHeritageProtectionBill.htm.

### 7.1 Access

Although geophysical survey is subject to the usual legal constraints concerning trespass there will be instances when a landowner's refusal to allow access can be overridden on the legal authority of a central or local government department. The contracted agents of the latter may thus be granted legal powers of entry, as stated for instance under Section 43 of the Ancient Monuments and Archaeological Areas Act 1979.

It should be noted that, where powers of entry can be invoked for the purposes of conducting an archaeological survey, these powers do not allow for the breaking of the surface of the ground. If construed literally, this ruling forbids the use of probes, augers and grid pegs. Soil samples may be obtained in some cases for engineering purposes, and these may be useful to the geophysical evaluation, but it remains illegal otherwise to break the ground surface without the landowner's permission. In all circumstances it is a responsibility of the contracting body to secure the goodwill of the landowner and thence the required permissions.

### 7.2 Metal detectors

Section 42 of the Ancient Monuments and Archaeological Areas Act 1979 states that the use of 'any device designed or adapted for detecting or locating any metal or mineral in the ground' in a protected place requires the written consent of the Secretary of State. Such consent, known as a Section 42 Licence, is obtainable direct from English Heritage and is required before the use of such instruments in the following categories of 'protected place':

- the site of a Scheduled Monument or of any monument under the ownership or guardianship of the Secretary of State or the Commission or a local authority by virtue of the Act;
- anywhere within an area of archaeological importance.

It is an offence to use a metal detector in such areas, to remove any metal objects so detected, or to fail to comply with any of the conditions of consent issued under a Section 42 Licence.

Further information and advice on use of metal detectors can be found in English Heritage (2006). Information on protected areas, including the location of Scheduled Monuments, can be found at: www.magic.gov.uk. Data on Scheduled Monuments in England can be obtained on request from nmrinfo@english-heritage.org.uk.

### 7.3 Geophysical survey

The restraints stated above also apply to the use of non invasive geophysical survey equipment. When such survey in a protected place is contemplated a written application for a Section 42 Licence must be sent to the English Heritage Inspector of Ancient Monuments (IAM) for the region.

The letter of application should provide full details of the proposed survey, including: the name of the monument affected, a plan of the area to be surveyed, objectives of the survey, a statement on the technique(s) to be used, make of instruments, names of individuals who will do the work and when the work will take place. The application will be considered by the IAM and may also be referred to the Geophysics Team (English Heritage, Fort Cumberland) for approval. Survey proposals should not usually encounter any difficulties in receiving consent, but applicants need to appreciate that the issue of a licence cannot be instantaneous and should therefore apply as far in advance as possible.

The Section 42 Licence will restrict the consent for survey to a clearly defined area and will be limited to named individuals or the nominees of a named individual or organisation. A condition of consent is usually that a copy of the survey report is sent to both the relevant English Heritage Regional Office and to the Geophysics Team (Fort Cumberland) within a fixed period (usually three to six months) after completion of the fieldwork. A date will be given after which the licence is no longer valid.

With the exception of 'Class Consents' (eg certain agricultural or forestry activities), any disturbance to the ground on a scheduled site, such as augering, requires Scheduled Monument Consent from the Secretary of State. In practice, small scale sampling of topsoil (<100g) obtained by augering or otherwise is usually acceptable under terms agreed in a normal Section 42 Licence. *Any* proposal for larger scale disturbance, whether to topsoil or subsoil, should be discussed with the IAM for further advice.

The above requirements are specific to England, although similar conditions apply in Wales and Scotland. For Wales, geophysical survey of scheduled sites requires prior written consent from Cadw, the Welsh Assembly Government's historic environment service. In Scotland, requests for permission should be made in writing to Historic Scotland which acts on behalf of the Scottish Ministers. There are no restrictions on geophysical survey in Northern Ireland, although ground disturbance at any archaeological site requires a licence from the Environment and Heritage Service.

Note that an Archaeological Licence Agreement is required for any surveys by a third party on National Trust (NT) property. Enquiries should initially be directed to the NT Archaeologist for the Region (see www.nationaltrust.org.uk/). Proposals will then need to be accompanied by a project design stating the aims of the project, a description of the methodologies to be used, its location, relevant previous research, proposed personnel, funding and a description of the relevance of the project together with an indication of its future application and publication. A risk assessment and proof of public liability insurance will also have to be provided. If approved, the NT Archaeologist will then complete and send two copies of the Archaeological Licence Agreement to the applicant for signing. Conditions will include the requirement that the licensee, upon completion of the survey, will provide a completed SMR form, a final report, copies of any resulting publication and copies of related records.

The operation of GPR equipment anywhere within the UK requires an appropriate licence issued by Ofcom and adherence to an agreed code of practice (*see* Part IV, 1.4.4 for full details).

# Part III
# Guide to Choice of Methods

## 1 Introduction

Geophysical survey should be thought of as one of the main techniques of site evaluation and its potential contribution must always be considered in each instance where development is proposed.

The purpose of the following section is to provide advice that will be helpful to archaeologists in determining whether or not a geophysical survey is required in a particular instance, and, if so, what techniques and methodologies may be the most useful to consider.

The choice of survey method(s) will vary with the site conditions, logistics and time constraints particular to each separate evaluation project. Adequate time should be allowed for the geophysical survey to be undertaken and reported on once this has been identified as a preferred evaluation technique. Clients must be assured that the appropriate methodology is being applied in each case.

## 2 Choice of geophysical survey

Geophysical survey is of course one of many possible approaches to the evaluation of archaeological potential, and its contribution must be appropriately balanced with others so as to optimise the project outcome. A typical combination might include data derived from aerial photography, map regression, geophysics, field walking and test-pitting. Ideally, data-sets such as these will be analysed and interpreted within a GIS environment.

It is obvious too, that within this broad concept of integration, geophysical survey itself offers a variety of approaches that can and should be used together to their mutual advantage. All projects need to give consideration to the full breadth of techniques that might be applicable to an evaluation, and to develop a specification that maximises their joint potential. For example, magnetometer survey may provide a distribution of pits, ditches and industrial features, but it will usually be necessary to combine this with more targeted earth resistance survey and/or GPR to identify building foundations. For the purposes of evaluation alone, however, it will often be sufficient for the choice of techniques simply to give an indication of the archaeological potential; the use of more elaborate integrated survey strategies will be a feature of research-led projects aimed at more detailed archaeological interpretation and towards advancing methodological development.

These guidelines are purposefully kept as brief and concise as the complexities of this subject allow. Choosing an appropriate survey strategy is never straightforward: it will depend upon the interplay of many factors, and will therefore vary from one site to another. It is rare that any one strategy can be singled out to the exclusion others, and different surveyors may well arrive at different procedures, each of which will have merit for different reasons.

It will be assumed that those who commission surveys will probably take specialist advice in each situation. The following tables are offered as a *rough preliminary guide* to the options that should be considered further.

The first guide to choice of survey offered here (Table 2) is in the form of a 'key'. Start at the top of the table with the first question and follow the directions in the right-hand column to sections further down the table, and so on, leading ultimately to a suitable survey option (or options) for the problem in hand.

**Table 2** Choice of geophysical survey: a key.

| | | *go to:* | *page:* |
|---|---|---|---|
| 1 | Is the site/area | | |
| | rural, semi-urban or | 3 | |
| | urban (built-up)? | 2 | |
| 2 | Try GPR (earth resistance and/or magnetometer survey may occasionally be appropriate, if conditions permit). | 7 | 14, 24, 28 |
| 3 | Are the archaeological features | | |
| | deep (>1.0m) or | 2, 11 | 16, 20 |
| | shallow (≤1.0m) or | 4 | |
| | very magnetic (eg kiln) | 10 | |
| | weakly magnetic? | 11 | |
| 4 | Is the geology | | |
| | metamorphic/sedimentary/drift or | 5 | 15 |
| | magnetic (eg basalt) or | 6 | 15 |
| | drift with magnetic pebble components? | 6 | 15 |
| 5 | Are the expected features mostly | | |
| | masonry/stonework or | 6 | |
| | cavities or | 2, 9 | |
| | large earth-cut features (eg channels, moats) or | 6, 10 | |
| | industrial features (including hearths, etc) or | 10 | |
| | ordinary earth-cut features (ditches, pits, etc) or | 10 | |
| | other burnt feature (eg building) | 10 | |
| | diffuse/small (ie not major earth-cut features) | 10, 11 | |
| | unknown? | 10 | |
| 6 | Try Twin Probe earth resistance | 7 | 24 |
| | GPR or | | 28 |
| | EM. | | 34 |
| 7 | Is it the possible site of a | | |
| | building or | 6 | |
| | a major linear feature (eg road, wall) | 6, 8 | |
| | features at depth (>1.0m)? | 9 | |
| 8 | Try earth resistance traverses, | | |
| | EM traverses or | | 34 |
| | EM area survey. | | 34 |
| 9 | Try electrical resistance tomography (ERT)/pseudo-section profiles. | | 24 |
| 10 | Try magnetometer area survey. | | |
| 11 | Consider magnetometer area survey using alkali-vapour instrument. | | |

Page numbers in the right hand column refer to pages elsewhere in the document where more detailed discussion is available: readers are cautioned not to accept a survey option without consulting the relevant sections of Part IV. The same advice applies to Table 3, which lists some of the most commonly occurring types of archaeological feature, and, alongside each, attempts to categorise the suitability of the main survey techniques for its detection in each case. Table 4 lists very generalised comments on the suitability of the major solid and drift geologies to magnetometer survey only (the responses of other geophysical techniques to differing geologies are less easy to categorise simply; where possible reference to these responses is made independently in Part IV).

In submitting these tables we must acknowledge that they are a considerable over-simplification and therefore reiterate that they are intended to serve only as a rough guide to choice of survey technique. Professional opinion varies on some of the attributions offered. For the moment, and into the foreseeable future, each situation will warrant specialist advice and this should be sought at an early stage in any project, once the general necessity for geophysical survey has been established.

The tables are followed by a more specific discussion of the survey options for a selection of commonly occurring evaluation scenarios. For those who wish to follow up aspects of technique and methodology in more detail we recommend consulting Part IV. Furthermore, valuable complementary information is available in the following publications: Clark (1996); Gaffney and Gater (1993; 2003); Gaffney, Gater and Ovenden (2002); Linford (2006).

## 3 Costs

Routine archaeological surveys are usually costed per hectare of area covered at standard sampling intervals. Such prices are usually inclusive of all aspects of the work and the supply of a report (and a specified number of copies of this). However, in some cases – particularly geotechnical surveys – quotations may not be all-inclusive and fieldwork may be costed per day on site with separate charges for data analysis and reporting. There may be a reduction if multiple techniques are carried out on a shared grid and concessions may be available if there is a research and/or publicity interest for the company concerned. Prices can vary significantly between different companies and will of course vary according to constraints peculiar to each site. Clients are advised to obtain a range of quotations for scrutiny. Care should be taken to establish whether or not VAT is included.

On completion of the tendering process it is good procurement practice for the client to name the successful contractor, to declare the range of prices received and to provide a list of tender applicants.

## 4 Urban (and brownfield) sites

The depth and complexity of most urban stratigraphy, closely constrained by modern intrusions, metallic contamination, services and adjacent structures, provides a near insuperable

**Table 3** Matching survey method to feature type: survey options (see key below): the choice of geophysical survey method(s) appropriate to a range of archaeological features, based on experience from the UK. Only the most commonly used survey methods are listed. This is a rough guide only, to which there will be exceptions, depending upon individual site circumstances and future technical developments.

| *Feature type* | *Mag area survey* | *Earth res survey* | *GPR* | *EM (cond)* | *Mag susc* |
|---|---|---|---|---|---|
| areas of occupation | Y | n | N | ? | y |
| below artefact scatters | Y | Y | N | ? | y |
| large pits (>2m diam) | Y | y | Y | ? | N |
| smaller pits (<2m diam) | Y | ? | y | N | N |
| ring gullies (prehistoric) | Y | n | N | N | N |
| post-holes (>0.5m diam) | y | n | y | N | N |
| hearths | Y | N | N | n | ? |
| kilns/furnaces | Y | N | ? | ? | ? |
| sunken-featured buildings | Y | y | ? | ? | N |
| house platforms | ? | y | n | ? | ? |
| ditches (<2m width) | Y | y | n | n | n |
| large ditches (>2m width) | Y | y | ? | ? | n |
| palaeochannels | y | y | Y | y | n |
| roads/tracks | y | y | ? | ? | n |
| robber/bedding trenches | y | Y | ? | N | N |
| timber structures | y | n | ? | N | N |
| masonry foundations | ? | Y | Y | Y | N |
| brick foundations | y | Y | Y | ? | N |
| paving/floors | – | Y | Y | ? | N |
| buried megaliths (mag) | Y | Y | Y | ? | N |
| buried megaliths (non-mag) | – | Y | Y | ? | N |
| stone-lined drains | n | y | Y | ? | N |
| other cavities | n | Y | Y | ? | N |
| graves | ? | y | ? | N | N |
| cremations | n | N | N | N | ? |
| ridge and furrow | Y | Y | N | n | n |
| lynchets | y | Y | N | n | n |
| waterlogged contexts | ? | ? | ? | ? | ? |

key:

Y The technique responds well in many conditions and is usually to be recommended.
y The technique can respond effectively in many conditions but is best used in conjunction with other techniques.
? The technique may work well in some conditions, and its use may therefore be questionable; another technique might be preferable.
n The technique may work in some conditions but is not usually recommended; another technique is usually preferable.
N The technique is probably not effective, or its effectiveness is uncertain.

deterrent to successful geophysical survey. An exception to this is when the survey is intended to detect the remains of industrial archaeology, which can often cause distinctive and strong anomalies.

Tightly constrained sites in heavily built-up areas do not usually offer suitable conditions for geophysical techniques, with the possible exception of GPR. This method is capable of detecting some types of archaeological feature (*see* Part IV, 1.4), and can also locate services and structural detail within building fabric. It is best applied when there is a measure of foreknowledge of what is sought, and preferably in conjunction with trial trenching or with coring.

Magnetometer survey over tarmac is possible only in exceptional circumstances. It may be possible over other types of paving but only in relatively unusual circumstances when no elements of the paved surface are strongly magnetic. Earth resistance survey is not possible over tarmac but electrical sections can be collected over other types of paved surfaces using plate electrodes and conductive gel or bentonite clay (Athanasiou *et al* 2007). Such surfaces are well suited to the use of GPR, however, and this technique can be considered for reconnaissance survey in the first instance where surface conditions preclude the use of other techniques.

**Table 4** Geology and the response to magnetometer survey.

| *Geology* | *Response to magnetometer survey* |
|---|---|
| Igneous | Thermoremanent effects can preclude survey over some igneous rock types (eg basalts); however, others (eg Cornish granites) seem to be relatively unaffected. |
| Metamorphic | Experience so far suggests that thermoremanence is not usually a significant problem and magnetometer survey can be effective (eg over gneiss and slates); but beware of adjacent intrusions. |
| Sedimentary: | Magnetometer survey can be recommended over any sedimentary geology. There are few significant distorting factors (but *see below* under drift) although a wide range of magnetic susceptibility in the parent rock results in a very variable background response to survey. |
| conglomerates/ grits/pebble beds | Response is average to poor (eg over Millstone Grit), but good in places, eg Devonian grits. |
| sandstones | Average response is poor, eg over some Old Red Sandstone and Mercian Mudstone; generally good over the Greensand, New Red Sandstone and some Tertiary formations. |
| limestones | Response is good, especially over Cretaceous Chalk, Jurassic and Magnesian limestones; less so over Carboniferous limestones. |
| mudstones/clays | Average response (London and Oxford Clays) is ?poor (eg Mercian Mudstone); but results can be very variable. |
| drift | *see below* |
| Drift: | Quaternary deposits overlying the solid geology are a primary consideration. They often show a high degree of local variation and the magnetic response is usually dependent on the magnetic mineralogy of the parent solid geology. |
| sands/gravels | Response is very variable; good on materials derived from Jurassic limestones and in parts of East Anglia; moderate to good in south-central England and in the west Midlands (Severn Valley). |
| coversands | Response is uncertain to ?poor. |
| boulder clay | Response is generally poor (eg in parts of East Anglia and northern England). |
| clay-with-flints | Response is good. |
| brickearth | Response is average to ?poor; better in SW England. |
| alluvium/colluviums | Response is average to poor, depending for instance on depth of burial of features below this material (see Part III, 6). |

On more open sites – rough ground, verges, gardens, allotments, playing fields, smaller parks, cemeteries, etc – the more traditional techniques can be applied, although experience shows that good results, while sometimes possible, are not often obtained. Surface obstruction or ground disturbance can prohibit sufficient survey coverage and mar the survey response, or both. Geophysical survey will not be justified in many circumstances, although magnetometer, earth resistance and GPR methods can be invoked when encouraged by specific expectations (eg of kilns, voids or wall foundations). Decisions on survey method and the interpretation of results must depend on as thorough a knowledge as possible of former land use. Trial trenching, coring and/or test pitting may well be a preferable approach in a majority of cases.

## 5 Cemeteries

Survey within *present-day* cemeteries, for whatever purpose, while sometimes called upon, is rarely very successful. Earth resistance traverses, and GPR, can be used, where space permits, to identify or confirm the course of features (usually wall foundations) the presence of which may already be suspected from other sources of information. Note that permission needs to be obtained from the church warden prior to survey.

A more common difficulty is the detection of *former* cemeteries or individual graves. None of the techniques described above can easily detect individual inhumation graves or cremations owing to their relatively small scale and lack of physical contrast between fill and subsoil. Stone lined coffins or cists may be detectable with earth resistance, or with GPR (Bevan 1991), using a narrow sampling interval (0.5m × 0.5m for earth resistance survey; 0.05m × 0.5m for GPR), but ordinary graves in rural situations are perhaps best sought with a magnetometer, also with a narrow sampling interval. The magnetometer response to ferrous items such as chariot fittings or individual weapons may give away the presence of graves, but it is not possible to tell the difference between these responses and those from irrelevant ferrous items.

Individual cremation burials may be detectable magnetically but the response is not normally distinguishable from background variations (nor, indeed, from anomalies from other types of feature of similar dimensions and magnetic characteristics).

Ferrous and non-ferrous items such as coffin nails and grave goods are detectable electromagnetically with metal detectors, the supervised use of which can be valuable in the detailed study of sites or of individual graves (David 1994).

Graves, cremations or cemeteries can therefore only be detected in very favourable conditions, often only indirectly, and when there is already good reason to suspect such features to be present. Geophysical evaluation, particularly over poorly known ground, will therefore easily overlook this important category of feature.

### 6 Alluvium

The detection of archaeological features at depths of >1m, whether covered by alluvium, colluvium, blown sand, peat or other material remains a major problem. Archaeology under river alluvium, in particular, has attracted much attention (Howard and Macklin 1999; Needham and Macklin 1992) and the problems encountered by geophysical techniques in these circumstances have been addressed by Clark (1992) and Weston (2001). The use of geophysical methods as part of a multidisciplinary approach to the geoarchaeological evaluation of deeply stratified sedimentary sequences has been addressed by a number of authors (see for example Bates and Bates 2000; Bates *et al* 2007; Carey *et al* 2006; Challis and Howard 2006; Powlesland *et al* 2006).

There can be no preferred recommendation until the merits of each individual site or area have been assessed. A pilot survey, linked with coring or test pitting can be invaluable in the subsequent development of a preferred full evaluation. Depths of alluvial cover, magnetic susceptibility values for the major sediment units, and local geomorphology will all have a significant bearing. Aggregates companies may have commissioned borehole and other surveys that can be helpful. British Geological Survey (BGS) (http://www.bgs.ac.uk/boreholes/home.html) and other specialist surveys may also be available. Information on mechanical coring as an aid to archaeological projects has been published by Canti and Meddens (1998) and by English Heritage (2007).

Magnetometer survey should usually be the method of choice (*see* Part IV, 1.2). Depending upon relative magnetic susceptibility values of the fills of smaller features, alluvium and subsoil, and the depth of burial, archaeological sites may be detectable up to 1m down (Clark 1992). The deeper the archaeology, however, the less likely to be resolved are small and poorly magnetised features. Magnetic anomalies show a tendency to broaden as they become more deeply buried by alluvium. While larger ditches, pits, hearths and kilns, etc may well be detectable at depths of 1m or more, the signal from smaller features will be too weak; many types of site – especially pre Iron Age ones and those without significant magnetic enhancement (eg most 'ritual' and many ephemerally occupied sites) – can be missed altogether.

Magnetometer survey should preferably target shallower alluviated areas, and their margins, and should, if possible, attempt to 'follow' detected features into areas of deeper alluvial cover, thereby enabling an estimate of 'fall off' in local detectability to be made. Close attention to available aerial photographic and microtopographical evidence is always essential (*see* Part IV, 1.10).

Survey with alkali-vapour magnetometers, which have an increased sensitivity over fluxgate instruments (*see* Part IV, 1.2), makes it possible to detect weaker signals from more deeply buried features. At present there are insufficient case studies available from UK sites to demonstrate a clear preference for one or other type of magnetometer. It seems inescapable, however, that the greater sensitivity of alkali-vapour instruments will offer an advantage over less sensitive instruments on sites where variations in topsoil magnetisation are minimal, as may be the case over some alluviated sites (Linford *et al* 2007). The degree of that advantage, and its archaeological significance, remains to be quantified and will, of course, vary from site to site. For the time being, the use of alkali-vapour magnetometers should at least be a consideration in evaluations of alluviated areas where magnetic targets are concealed at depths of >1m.

If magnetometer survey is ineffective there may be some justification in attempting earth resistance survey over suspected structural remains, but problems of resolution at depth (>1.0 m: Clark 1992), as well as the costliness of extensive survey, can be prohibitive. Electrical sections, using widely spaced electrodes (>1m) can be of value in plotting the larger-scale features of the sub-alluvial surface (Bates and Bates 2000), although GPR, under suitable conditions, is probably a more flexible and rapid method (*see* Part IV, 1.4).

Area survey of topsoil magnetic susceptibility can indicate general areas of artificial enhancement derived from shallow archaeological horizons and may be useful for directing subsequent magnetometer survey. Magnetic susceptibility data may also help map the alluvial edge if this is not otherwise evident from other data. Augering to obtain samples from sub-surface horizons should be done to obtain control measurements, but this is usually too time consuming for any extensive area survey of magnetic susceptibility, phosphate or other soil component. Such detailed work would, in any case, probably be inappropriate in the majority of commercial evaluations.

EM survey (conductivity and magnetic susceptibility) can be used to identify features of gross geomorphology under alluvium, but does not yet seem capable of detecting even the moderate detail of archaeological features buried at depth. Low-frequency GPR (<200MHz) can also detect features such as palaeo-channels and gross stratigraphy but the signal attenuation of higher frequencies in conductive soils either prevents or seriously inhibits the detection of smaller archaeological features (*see* Part IV, 1.4).

In summary, alluvial and other types of superficial deposits present serious difficulties for geophysical prospecting. These are accentuated at depths in excess of a metre. For large areas, a pilot survey can be conducted, testing the suitability of various techniques, although the emphasis may often turn out to be on magnetometer survey. Other survey techniques, such as GPR, can be used more selectively but at present none can be recommended as an adequate general technique in these conditions. While some archaeological sites may well be detectable from the surface, it remains true that many others, perhaps even the majority, will remain elusive until made visible by more direct intervention. However, the ability to detect larger-scale geomorphological features, such as palaeo-channels, and the value these may have for indirectly predicting the presence of archaeologically significant deposits, must not be underestimated.

As things stand, whereas geophysics may be helpful in some circumstances, archaeological evaluation over deeper alluvium (>1m) should rely on a combination of field techniques centred on a scheme of test trenching, possibly assisted by lidar (*see* Part IV, 1.10.3).

### 7 Wetlands

The problems of depth of burial, as above, are accentuated by waterlogging. The only technique that at present seems to offer any potential is GPR over low mineral content peat. At low frequencies (eg 100MHz) the peat/mineral interface of peat basins is detectable at depths up to about 10m (Theimer *et al* 1994; Utsi 2001), and reflections have also been recorded from substantial objects such as bog oaks (Glover 1987). Some case studies (eg Clarke *et al* 1999) indicate that GPR is also capable of detecting potentially significant anomalies within peat, and there are reports that wooden trackways or other structures may be detectable (Jorgensen 1997; Utsi 2001). Although such accounts are promising, there is a need for further experimentation, and reference to ground-truth, before GPR can be recommended as a routine approach in these circumstances. In other types of wetland, in clay or saline situations, GPR and other techniques are ineffective at locating organic structures.

Geophysical techniques can, as yet, have little part to play in wetland evaluation. Structural remains (such as pile dwellings, trackways, etc) in organic sediments, in particular, are often undetectable. Traditional dry land geophysical techniques are best attempted in areas of relative dryness and shallow overburden ('islands' or wetland margins) and features so detected may then have some indirect bearing on the likely location of significant sites elsewhere obscured. Aerial photography, lidar and remote sensing (Cox 1992; Donoghue and Shennan 1988), linked with augering and test trenching can offer the best overall evaluation, geophysics being drafted in for the examination of specific shallow or marginal sites.

It should be noted that magnetic susceptibility readings on waterlogged material can be suppressed by chemical changes (Thompson and Oldfield 1986). Magnetic susceptibility signals will persist in some lacustrine and intertidal deposits, however (eg Linford 2003).

## 8 Road and pipeline corridors

The need to evaluate linear corridors traversing many kilometres of countryside in advance of the building of pipelines, new roads or the upgrading of existing routes, continues to create considerable demand for non destructive evaluation (Lawson 1993). Geophysical survey thus has a crucial role, and although the general rules of survey as outlined elsewhere in these guidelines apply, the special problems of survey logistics, and the choice of an appropriate balance of survey methodology, suggest that a separate consideration is needed. Specifically, while linear corridors may be comparable in total area to the very large development areas described below in section 10, their narrow lateral extent makes them particularly amenable to detailed survey over the entire development area using modern survey methodologies. Hence the considerations in this section override those described below for extremely large development areas in general.

It is stressed that the following recommendations are general and do not attempt to set out a rigid procedural blueprint. As for any call upon geophysical survey, individual site conditions will dictate a survey procedure that must be expected to vary from one instance to another. Inevitably, too, different survey specialists will favour slightly different approaches. The following attempts to set down basic considerations that should be common to all.

Linear developments are complicated by the large and extended area of land affected and by the variety of geological and soil conditions through which the route will inevitably pass. Geophysical survey may often play a unique role in the evaluation of archaeological remains threatened by linear developments and should be conducted at an early stage in the planning process, when consideration of the results may mitigate the route of the development to take account of significant archaeological features. While it is acknowledged that the destruction caused by the linear development is the main concern, consideration should also be given to the impact of the development on obtaining geophysical data in the future. In particular, ferrous pipelines will produce a large area of magnetic disturbance, up to 20m either side of the pipe, which will compromise the subsequent acquisition of magnetic and electromagnetic data.

A balance must be met between the cost of obtaining adequate geophysical coverage, the impact of the proposed development and the anticipated benefits of the survey results.

The following specific points should be addressed:

(1) The proposed geophysical methodology should be appropriate for the location of archaeological remains along the route of the linear development. The results of previous geophysical surveys conducted under similar conditions should be considered when recommending both instrumentation and sample intervals; note that a single technique may not be suitable for the entire length of the proposed development.
(2) Detailed area survey over a closely sampled grid is to be preferred over any unrecorded (eg magnetometer scanning) or low sample density recorded methods (eg topsoil magnetic susceptibility). In all cases single long traverses should be avoided.
(3) The area covered by such detailed survey should be sufficient to encompass the entire easement of the development and any additional areas where damage to underlying archaeological deposits may occur (eg plant access routes).
(4) If possible, the survey transect should also be of sufficient width to characterise adequately the archaeological potential of significant geophysical responses, particularly linear anomalies, traversing the route. This may save the need for any subsequent requirement for additional survey to further define enigmatic anomalies.
(5) The recent introduction of multi-sensor geophysical instruments and platforms, combined with GPS, has significantly increased the rate of field data acquisition. As a result, areas that in the past would have been considered so large that they could only be partially sampled, are often now amenable to rapid and cost-effective detailed magnetometer survey in their entirety.

Providing no overriding geophysical contra-indications exist (eg unfavourable geology or soils, preponderance of modern ferrous interference, etc), then magnetometer survey should provide the most cost-effective method of evaluation. A sample density of at least 0.25m × 1m should be used, which can be collected rapidly in the field using a multi-sensor instrument.

Other geophysical techniques would not usually be deployed blind over large parts of a linear development and the considerations for their effective use are the same as for any exceedingly large evaluation area (*see below*, section 10).

The width of the corridor to be evaluated using geophysics will depend on the particular linear development in question. However, in the case of pipeline developments, given the typical easement width and the area excluded from subsequent survey by the presence of the ferrous pipe or embankments, a minimum linear transect width of 30m would commonly be suitable. For road corridors the maximum width is normally between 40m and 100m, and this should always be completely covered. Agreement should be reached with the client as to whether or not a broader coverage to either side of the corridor may be allowable in order to place features within their broader context. Broader coverage may also be of benefit to the development, identifying potential alternative routes to be planned around areas where archaeological remains are identified. Clients or their agents should certainly be strongly encouraged to allow for such contingencies, following appropriate consultation.

## 9 Wind farms

Wind farms are a relatively new form of development designed to generate electricity from a sustainable resource. They require the construction of a group of turbines usually on a site in an elevated, exposed rural area. Owing to their nature, it is necessary for the turbines to be dispersed relatively widely across the landscape and each needs a firm foundation set into the ground. When considering geophysical evaluation of wind farm sites, it is preferable that the entire area over which the turbines are to be distributed is surveyed in detail using magnetometer survey. If areas of particular archaeological potential are identified, targeted follow-up survey with more intensive techniques such as earth resistance and GPR can then be used, as for other forms of development. With a full survey over the whole site it should be possible to select individual turbine positions so that the most archaeologically sensitive areas are avoided.

However, if turbine positions are constrained and the area of the entire site is so large that it is considered unreasonable to survey it all in detail, then consideration should be given not only to the physical foundation of each turbine but also to its magnetic footprint when installed. Wind turbines are typically tall steel structures that cause strong local magnetic fields, which will influence sensitive magnetometer measurements made in their vicinity. Once in place it will not be possible to detect archaeological remains using a magnetometer within a radius of about 30m of the turbine. It is thus recommended that, at minimum, detailed magnetometer surveys of 100m by 100m areas be carried out centred on each turbine position before their emplacement.

### 10 Extremely large areas

In some cases the total extent of a development area may exceed the area that can be reasonably surveyed in detail (that is, at a maximum sampling interval of 0.25m × 1m for magnetometer survey and 1m × 1m for earth resistance survey). What is deemed to be reasonable will of course represent a finely balanced equation between several factors, not least of which will be the available resources and the previously established archaeological sensitivity of the areas in question. The archaeological factor should always be the prime consideration.

A preliminary essential is that the survey potential of any area is assessed in the light of existing desktop knowledge. Where the priorities for survey are not then obvious, and especially in the case of large areas (>20ha), a pilot magnetometer survey can be carried out before any further commitment to major outlay of resources. Further preliminary field trials to assess response to local conditions may also be warranted, and these could include magnetic susceptibility sampling, magnetometer scanning or sample earth resistance survey, as well as tests with EM or other specialised survey techniques (eg GPR).

In rural, semi rural, and many other open areas, where magnetic interference is not prohibitive, there is usually no good reason not to undertake detailed magnetometer survey over the entire evaluation area, covering at least the ground that will be destroyed or damaged by the development. Increased archaeological sensitivity, or other pressures, may demand that larger areas are covered in detail.

Earth resistance survey will not normally be undertaken blind over large areas, and will only be applied where such survey is clearly called for on the basis of independent evidence (Part IV, 1.3).

In exceptional circumstances, where full detailed survey is deemed not to be practicable, a compromise between this and less intensive sampling may be required, justified by the commissioning body. In these cases, again, magnetometer survey should usually be a priority consideration. The following approaches may apply:

(1) detailed geophysical survey of priority sites already identified by desktop study; then, once such sites have been accounted for, …
(2) magnetic susceptibility survey of blank areas (or the entire area if necessary), at a maximum sampling interval of 10m, followed by selected magnetometer or earth resistance survey of areas of magnetic enhancement;
(3) magnetic susceptibility survey with systematic sampling by detailed magnetometer coverage;
(4) augering should be allowed for, both to obtain samples and to aid the direct interpretation of specific anomalies.

Survey procedures should follow the recommendations given in Part IV, 1.
The following cautions apply:

(1) Single long traverses of magnetic susceptibility measurements must be avoided and several parallel traverses separated by a distance similar to the measurement interval along the traverse should always be recorded.
(2) Single earth resistance or magnetometer traverses are not acceptable.
(3) Magnetic susceptibility measurements must always be followed up by complementary and more detailed survey in areas of enhancement. Some areas lacking enhancement must also be tested in this way to demonstrate that, for the area in question, variations in magnetic susceptibility are primarily caused by the presence or absence of archaeological remains and not by changes in other factors such as geology or recent land use. To assist interpretation, magnetic susceptibility values for different subsoil types should be obtained for comparison against topsoil values. If necessary this relationship can be further examined by comparison with fractional conversion measurements.
(4) If there are any exceptional circumstances making it impossible to evaluate an entire development area using detailed area survey over a closely sampled grid, it is still desirable for at least 50% of the total area to be sampled with detailed measured survey, with the remainder sampled by one or more of the methods referred to above.

# Part IV Practitioner's Guide to Good Practice

## 1 Application of techniques

### 1.1 The survey grid

Geophysical fieldwork relies on the presence of an accurately plotted network of control points extending across the area to be worked on and this is usually referred to as the survey grid. An internally accurate and correctly georeferenced grid is crucial to all subsequent survey and to the whole project outcome: close attention to this fundamental stage of fieldwork is therefore essential. Recent developments involving mobile sensor platforms incorporating real time global positioning system (GPS) sensors mean that it is no longer always necessary to establish a conventional grid of fixed markers over the surface of the area to be surveyed (*see below*, section 1.1.2). When employing such technologies, survey teams should recognise that a grid of control points capable of accurately defining the boundaries of the area surveyed is still required even if not actually laid out with ground markers before or during the geophysical survey.

However the survey grid is located, during fieldwork a record should be made relative to it of surface conditions and sources of modern geophysical interference that might have a bearing on subsequent interpretation of field data.

#### *1.1.1 Conventional survey grids*

Establishing and marking out the survey grid are usually the responsibility of the project manager, although this should be discussed and clarified with the geophysical survey team involved. The grid can be laid out by any suitably qualified personnel with the agreement of (and, if necessary, following the instructions of) the geophysical surveyors. Considerations of geophysical methodology or ground response may well dictate a preferred grid alignment, particularly when the alignment of linear features is already known. In this regard, Gaffney and Gater (2003, 85–8) provide a concise review of the issues common to most archaeological geophysical surveys.

Where deadlines are tight, a previously surveyed grid will allow the incoming geophysical survey team to concentrate their specialist time to greater effect. Where more time is available, they may otherwise wish to provide the survey grid themselves. Whoever lays out the grid, it is important that its internal accuracy and measurements to fixed topographic points are rigorously and independently checked. Geophysical survey teams are advised always to check the accuracy of previously surveyed grids and to take independent measurements for grid location. There can be no excuse whatsoever for any subsequent mismatches between different parts of a geophysical survey, or other positional confusion. It is preferable and convenient, but not essential, for the geophysical survey grid to match exactly the Ordnance Survey National Grid (see for example English Heritage 2003) or a site grid devised for other purposes, such as field walking. The need to fit a survey into existing boundaries may dictate the use of a different grid, however. If more than one grid must be used, accurate location of each will be critical for the subsequent integration of results.

A unit of either 20m or 30m for the side of each grid square is usual (although some survey methodologies may use a different optimal base survey unit), with grid intersections located on the ground using wooden pegs or other temporary markers, which must be non-magnetic for magnetometer surveys. Because of the many hazards involved, not least of which concern the safety of people and animals, the choice of markers and their duration in the ground needs careful forethought as well as the agreement of the landowner and/or tenant (*see also* Part I, 7.1).

The grid must be laid out using currently accepted conventional methods (eg Bettess 1992; Bowden 1999; Clark 1996).

For long grid lines, in excess of 100m, the use of a theodolite, EDM total station or GPS is advisable. For smaller grids, the use of an optical square is acceptable (eg English Heritage 2002). English Heritage (2003, 8–9) provides a useful summary of the different types of measurement accuracy associated with survey grids, defining relative, map and absolute accuracy. Using any of the aforementioned techniques it should be possible to locate the grid control points on the ground to a relative accuracy of ±0.1m. GPS equipment is becoming increasingly available and English Heritage (2003) addresses the issues associated with its use for archaeological survey, classifying the various types of GPS system according to the positional accuracy that can be achieved (navigation-grade, map-grade and survey-grade). Survey-grade GPS, capable of absolute positional accuracy of ±0.1m (either in real time or with post-processing), is the only grade suitable for locating survey grid control points. It should be noted that the positional accuracy of existing base maps may be lower, depending on how they were originally created (see English Heritage 2003, 8–9). Bearing this in mind, it is advisable when using GPS to locate the survey grid to measure the positions of some fixed local landmarks or boundaries recorded on the area base map and not just record the temporary survey grid points. Any discrepancies between GPS positioning and local base mapping can then be compensated for and it is also possible to re-establish the grid independently relative to the measured landmarks.

#### *1.1.2 Interfacing with GPS*

Recent developments in GPS technology mean that it is now possible to interface geophysical survey instruments directly to continuously logging mobile (portable) GPS sensors, enabling the position of each measurement to be accurately located as it is taken (Fig 1). A differential GPS system may be employed to position measurements rapidly relative to a field-based control station, which is subsequently georeferenced to provide absolute accuracy through post-survey processing. However, the most recent real-time GPS systems can provide immediate survey-grade absolute accuracy by receiving broadcast signals from real-time correction signal transmitters calculated from a network of fixed control stations. With both types of GPS system, it is possible to carry out an accurately positioned geophysical survey without first establishing a physical grid of ground markers. It is important for the users


**Fig 1** (above) The GEEP towed mobile sensor platform with built-in GPS (photograph courtesy of Ian Hill, University of Leicester).

of such systems to be aware that the same considerations apply with respect to the georeferencing of the survey area, as when GPS is used to position a conventional survey grid. For instance, the speed of data acquisition might dictate that it is not possible to position every geophysical measurement directly to survey-grade GPS accuracy. Because of such considerations the boundaries of the survey area must be accurately georeferenced to the same standard as would be expected when a conventional survey grid is employed.

Portable GPS sensors mounted in a backpack or on a mobile sensor platform (section 1.7.7) afford freedom from the need to establish a grid of fixed control points and then surveying a series of regular parallel traverses between them. However, with respect to geophysical survey two considerations should be borne in mind. Many geophysical instruments have a response that is conditioned by their direction of travel (eg magnetometers) and subtle archaeological anomalies may not be distinguishable in a survey where random measurement errors are introduced by frequent changes of direction. For this reason, a completely 'random walk' data-acquisition strategy is usually inappropriate for geophysical surveys. An even density of measurements should also be achieved over the whole survey area, avoiding dense clusters of measurements in some parts and very wide gaps between measurements in others.

One way to avoid both problems is to emulate the parallel, evenly spaced, traverses employed in conventional surveys either by using a portable navigational control linked to the GPS system or by establishing a series of regularly spaced aiming points at the edges of the survey area. When employing such methods to ensure even coverage, care should be taken to avoid veering too far off-line when surveying each traverse as this could result in overly wide gaps between adjacent traverses resulting in a lack of geophysical coverage in the intervening area (Fig 2a). To demonstrate that an even coverage has been achieved when not using a conventional grid, the point cloud of measurement positions should be plotted on the base map in the survey report (eg Fig 2b).

## 1.2 Magnetometer survey

### *1.2.1 Choice of magnetometer survey*

Magnetometer survey offers the most rapid ground coverage of the various survey techniques and responds to a wide variety of anomalies caused by past human activity. It should thus be the first technique considered for detailed survey of an area and other, slower, techniques should usually follow afterwards, targeting smaller areas of interest identified by the wider magnetometer survey.

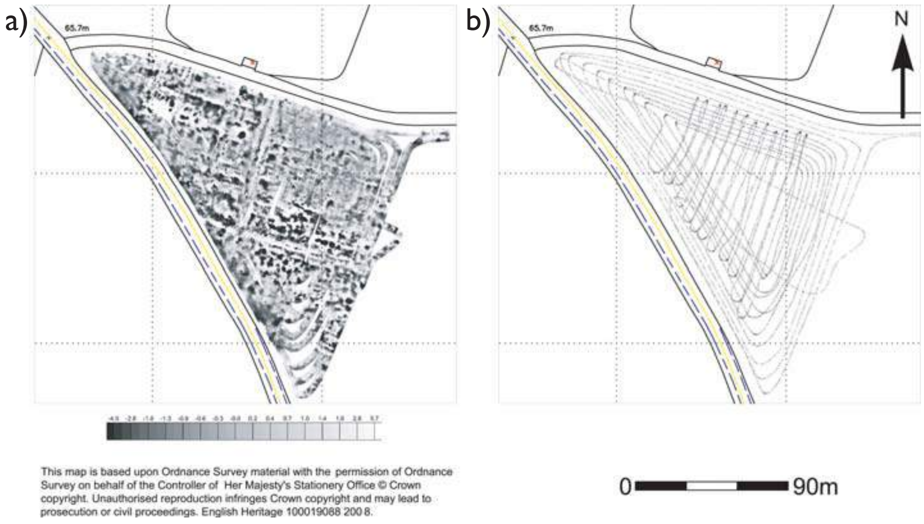




**Fig 2** (above top) Some preliminary field trial data collected at Wroxeter Roman city using the system pictured in Fig 1: (a) Greyscale plot of the caesium magnetometer results, which clearly show part of the Roman city plan; this data compares well with hand-held magnetometer data collected over the same area using a more traditional, but much slower, survey methodology. (b) Plot of the on-board GPS measurements showing the track of the system around the field; this was a rapid trial to test different survey methodologies and the southern corner of the survey, where gaps are visible between the magnetometer transects in (a), highlights the importance of ensuring even data coverage when not surveying on a regular grid (data courtesy of Ian Hill, University of Leicester).

**Fig 3** (above bottom) Handheld magnetometer systems: (a) Geoscan FM36; (b) Geoscan FM256 in dual sensor configuration (photograph courtesy of Roger Walker, Geoscan Research Ltd); (c) Bartington GRAD601 dual channel fluxgate system; (d) Scintrex SM4G Caesium magnetometer; (e) Foerster FEREX 4-channel fluxgate system (photograph courtesy of Norman Bell, Allied Associates Geophysical Ltd).

**Fig 4** (right) Cart mounted magnetometer systems: (a) Four Scintrex SM4 caesium sensors mounted at 0.5m intervals; (b) two Geometrics G858 sensors mounted at a 1.0m interval (photograph courtesy of ArchaeoPhysica Ltd); (c) Foerster Ferex 4.032 4-channel fluxgate system with sensors mounted at 0.5m intervals (photograph courtesy of Institut Dr Foerster); (d) two sets of SQUID gradiometers mounted at a 0.5m interval.

**Fig 5** (far right) Greyscale plots of caesium (a) and fluxgate (b) gradiometer data acquired over the same series of Roman enclosures at the same sample intervals (0.5m traverse spacing and 0.125 measurement intervals along traverses). Instrumentation: Scintrex SM4G and Bartington Grad601 sensors in 1m vertical gradiometer configuration.

It can identify thermoremanently magnetised features such as kilns and furnaces as well as in-filled ditches and pits and areas of industrial activity (both recent and ancient). Unless composed of materials that contrast magnetically with the surrounding soil (eg bricks carrying a thermoremanent magnetisation), magnetometers do not usually detect wall footings directly and in this regard it is complemented by earth resistance survey.

### *1.2.2 Instrumentation*

The prime workhorse for routine magnetometer survey in UK archaeological evaluation is the fluxgate gradiometer. This instrument combines sensitivity of the order of 0.1nT with lightweight design and rapid measurement rates, and several commercial systems are now available in the UK. However, alkali-vapour magnetometers are now becoming popular having long been routinely used in continental Europe. These instruments may also be named optically-pumped or caesium magnetometers (although at least two other alkali metals – potassium and rubidium – can also be used). They offer sensitivities of the order of 0.05 to 0.01nT and can make measurements at similar rates to fluxgate systems. The commercial fluxgate and alkali-vapour systems most commonly employed in the UK are listed in Table 5 and a number are pictured in Fig 3.

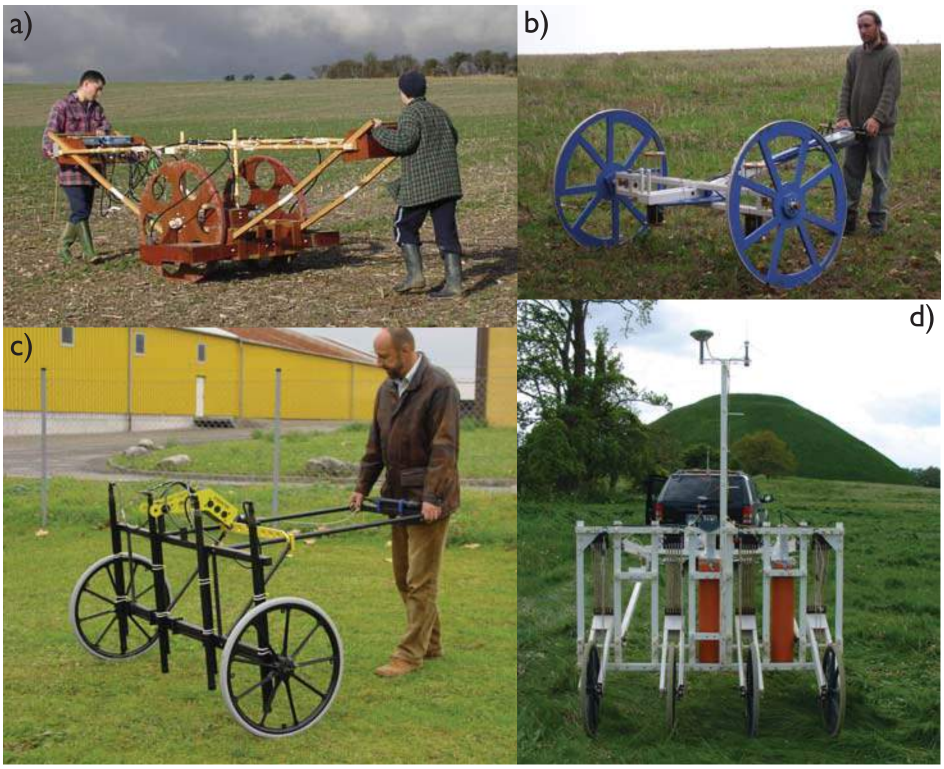
The main practical difference between the two types of instrument is that an alkali-vapour magnetometer measures the total absolute magnitude of the local magnetic field, while a fluxgate gradiometer measures the relative difference between the magnitude of the vertical component of the local field measured by two sensors positioned one above the other (separated typically by a distance of 0.5 or 1m). When required, it is possible to configure an alkali-vapour magnetometer as a gradiometer by differencing the measurements made by two separate, appropriately mounted, sensors (although in this case it is the vertical gradient of the total magnetic field that is measured). In general, alkali-vapour instruments are more sensitive (Becker 1995) but it is usually necessary to mount them on some form of mobile platform or cart (Fig 4a–b) – thus reducing sources of random measurement errors – to take full advantage of their enhanced sensitivity. In practical terms, for a typical site at UK latitudes, differences between the two instrument types in resolving the primary archaeological features appear to be relatively minor (Fig 5) and the principal requirement is that the magnetometer should have a measurement sensitivity of 0.3nT or better.

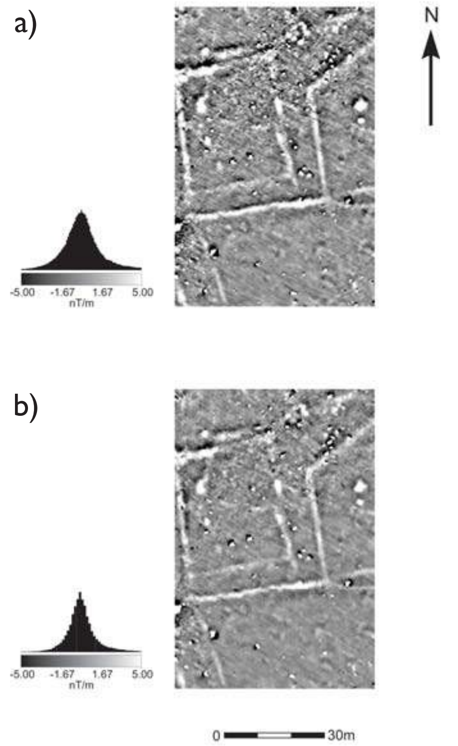
It may be remarked that other types of magnetometer are also available (eg proton, Overhauser); however, their use for routine survey would require special justification. Whatever type of magnetometer is employed, the operator should be fully familiar with the manuals supplied with it (and any updates provided by the manufacturer) and should rigorously apply the recommendations for equipment maintenance and survey procedure.

A number of manufacturers have adapted their systems to allow multiple sensors to be mounted horizontally in parallel. This enables two or more traverses of data to be collected simultaneously, increasing the speed at which surveys may be carried out. While this is a relatively recent innovation in the case of most fluxgate systems (Fig 3b, c and e), multiple alkali-vapour systems, often deployed on custom-built carts have been in existence for some time (Fig 4a–b). Cart-mounted arrangements are also now being developed for some fluxgate systems (Fig 4c). For any type of magnetometer, these offer the benefits of reduced random measurement noise and rapid area coverage (a larger number of sensors may be mounted in parallel, typically enabling four to six multiple traverses to be measured simultaneously, potentially with an integral GPS for positioning). Set against this, carts can be more restricted in the types of terrain in which they can operate as compared to light-weight, hand-held instruments, especially where the survey area is small and constrained, so a range of field conditions can mitigate in favour of the latter (Gaffney and Gater 2003, 68–72).

### *1.2.3 Methodology*

Before beginning a survey the magnetometer must be correctly prepared for use. Most magnetometers require some warm-up period before they settle into stable operation. This is typically of the order of five minutes for alkali-vapour instruments but fluxgate gradiometers, being more sensitive to differences in temperature, typically require about twenty minutes to adapt fully to site conditions. Most fluxgate gradiometers must then be 'balanced' (aligning the two fluxgate



sensors along the vertical axis) and 'zeroed' (calibration of the measurement scale for the local conditions). This procedure should usually be done over an area of uniform magnetic field, preferably using the same location throughout the survey. Particular care must be taken in the selection of this location when calibrating dual- or multi-sensor instruments as a proportionally larger area free of local magnetic field perturbations is required.

The operator must remove all sources of magnetic interference from his or her clothing (note: coins cannot now be assumed to be non-magnetic). Particular care must be taken to ensure that footwear is not magnetic and that even small extraneous ferrous items (staples, studs, tags, springs in zippers) are not present in clothing. Note also that magnetic material (including excessive amounts of soil) can become attached to footwear (and sometimes even to the instrument itself) during the survey and can adversely influence the magnetometer signal where the soil is strongly magnetic. Clients should appreciate that there are some circumstances (eg soil on footwear) that cannot be easily avoided and may therefore result in a slight deterioration in data quality.

Field conditions may dictate the type and configuration of magnetometer that it is most practical to employ. A cart-based system may be of limited use in a confined area. Gradiometers discriminate more strongly than total-field systems in favour of anomalies in close proximity to the sensors (Breiner 1999, 50–1). This property can limit the maximum depth at which features can be detected and total field systems are perhaps more suited when remains are expected to be deeply buried (eg alluviated environments). However, gradiometers can survey in closer proximity to modern ferrous objects such as wire fences or pylons. Indeed, this configuration is often the only way to carry out a magnetometer survey near a busy road as it reduces the effect of transient magnetic anomalies caused by passing vehicles, which cannot be readily filtered out by post-processing. Most archaeological features will produce weak magnetic anomalies, so magnetometers with several range settings should be set at their most sensitive and certainly ought to be configured to measure differences of the order of 0.1–0.3nT. However, in some instances (eg when surveying over industrial archaeology or substantial kilns or furnaces) reduced sensitivity may be necessary to avoid saturating the sensors when mapping very high magnitude anomalies.

Given the relative rapidity (and thus cost-effectiveness) of modern magnetometers, the preference should be for a detailed magnetometer survey of the entire area subject to evaluation. The area to be surveyed is typically divided into a series of regular square or rectangular blocks or sub-grids (*see above*, section 1.1.1) and each is then methodically surveyed by conducting a series of equally spaced parallel traverses across it with the magnetometer. Measurements are recorded at regular, closely spaced, intervals along each traverse. This is usually achieved by setting the instrument to take readings at fixed time intervals and using an audible time signal to ensure an even pace, or by recording fiducial markers at regular distances so that variations in pace can be subsequently corrected for. However, as noted in section 1.1.2 *(above)* some recent magnetometer systems can integrate directly with a GPS system to log the position of each measurement directly and obviate the need for a pre-established survey grid.

For detailed area survey the maximum separation between measurements along a traverse should be no more than 0.25m. Clark (1996, 80–1) considers the sample resolution necessary to discriminate between near surface ferrous objects and more deeply buried archaeological features and concludes that a sample separation of 0.25m enables full characterisation of anomalies with minimal distortion to their shape. Schmidt and Marshall (1997) examine the same problem from the perspective of the sampling theorem. They conclude that the sampling interval should not exceed the burial depth of the features being searched for. As the shallowest features may be in the topsoil, typically some 0.2–0.3m beneath the magnetometer sensor, a sample interval of 0.25m is again recommended.

Modern magnetometers such as those listed in Table 5 can sample rapidly (~10 times per second), have data loggers with large internal memory capacities, and can quickly transfer stored data to a computer. Hence, sample density along traverses has relatively little impact on the time taken to survey an area. However, the same is not true of the separation between traverses where the time taken is inversely proportional to the traverse separation (closer traverse separation increases the number of times the magnetometer must be traversed across the area to achieve the necessary coverage). Practicality dictates that some compromise is necessary and, for evaluation surveys, where the primary goal is to establish the presence or absence of archaeological remains, the maximum acceptable separation between traverses is 1m. Clark (1996, 81) notes that dense measurement along traverses is usually effective for characterising the nature of features so that it is then often sufficient only to establish their extent in the cross-traverse direction.

However, where it is necessary for the survey to identify smaller discrete features, such as postholes, a closer traverse separation should be used and 0.5m is recommended. Fig 6 illustrates the resolution of magnetometer surveys at a variety of sampling densities over two circular arrangements of postholes. The most dramatic increase in the ability to resolve the anomalies caused by these small features

**Table 5** Selected magnetometer models and manufacturers by type.

| *Manufacturer* | *Model* | *WWW URL* | *Resolution* | *Multi-sensor?* |
|---|---|---|---|---|
| *fluxgate gradiometers* | | | | |
| Bartington Instruments | Grad601 | http://www.bartington.com/grad601.htm | ~0.3nT | single and dual sensor versions |
| Foerster | FEREX 4.021 | http://www.foerstergroup.com/UXO/ferex.html | ~0.3nT | 4 sensor frame available |
| Geoscan Research | FM36 & FM256 | http://www.geoscan-research.co.uk/page71.html http://www.geoscan-research.co.uk/page28.html | ~0.3nT | single and dual sensor versions |
| *alkali-vapour magnetometers* | | | | |
| Geometrics | G858-G | http://www.geometrics.com/858-d.html | ~0.03 to 0.01 nT | single and dual sensor versions |
| Scintrex | SM4G | – | ~0.03 to 0.01 nT | single and dual sensor versions |

is achieved when the traverse separation is reduced to 0.5m. The commensurate increase in survey time required to cover areas at this greater traverse density can be reduced by the use of multi-sensor systems such as those pictured in Fig 4. Multiple alkali-vapour sensors can be mounted at separations of 0.5m, while a similar effect can be achieved with fluxgate sensors fixed 1m apart by the use of interleaved traverses (eg see Gaffney and Gater 2003, 65).

Boundaries such as hedges and fences will often constrain the orientation of the survey grid. However, where possible, it is preferable for traverses to be walked at right angles to the direction of recent ploughing to minimise any adverse effects of the latter on subsequent plots. Where the alignment of anticipated linear archaeological features can be predicted in advance (perhaps from air photographic or earthwork evidence), it is again preferable to avoid orienting traverses in this direction. Linear anomalies parallel to magnetometer traverses can be inadvertently removed by processing to counter the directional sensitivity of the instrument. At all latitudes the greatest peak-to-peak magnetic anomaly is obtained in the north–south direction (Breiner 1999, 41). So, when employing a sampling interval along the instrument traverses narrower than the separation between them and if there are no other constraints on traverse orientation, a north–south orientation will achieve optimal benefit from the anisotropic sample density.

Fluxgate magnetometers can exhibit excessive sensitivity to motion-induced errors when oriented in a particular direction to the Earth's magnetic field, the direction being specific to each instrument. Taking traverse direction into account, care should be taken to avoid surveying with the magnetometer while oriented in this adverse direction, changing the way the instrument is carried if necessary. A similar consideration applies with respect to alkali-vapour sensors, which are insensitive to magnetic fields in directions aligned too closely to a particular direction dictated by the sensor's geometry known as the tumble angle. Again, care should be taken to ensure sensors are aligned appropriately for the local magnetic field direction. Remedies for sensor orientation problems tend to be instrument specific and the relevant manufacturer's manual should be consulted in each case.

Instrument traverses may be recorded in either 'zigzag' or 'parallel' fashion (Gaffney and Gater 2003, fig 10), with data logger settings and subsequent data handling varying accordingly. While zigzag traverses enable the most rapid ground coverage, there can be a tendency for the response of alternate traverses to be offset with respect to one another. This can occur when the magnetometer is not held in the correct relative position or because of an incorrect walking pace relative to an odometer rate. The effect is often most pronounced when traverses run up and down slopes and results in linear anomalies at right angles to the traverse direction being 'staggered' and producing a herring-bone pattern. The worst effects of this problem can be eliminated by post-processing, but are often difficult to remove entirely. Hence for portions of a survey over particularly difficult terrain, parallel traverses should be considered and in all cases care should be taken to eliminate the effect as far as possible by correct data collection procedures.

Continuous-reading magnetometers may also be used for scanning. The instrument is carried along traverses spaced and oriented according to local requirements without logging the signal (Clark 1996, 83–91; Gaffney and Gater 2003, 93–4). Its output is observed by the operator and anomalies marked, then further investigated by more intensive scanning or by detailed recorded survey and/or augering. However, the method depends for much of its success on the experience of the operator, and even the most skilled surveyors are unlikely to be able to detect, by scanning alone, dispersed or weakly magnetised features (and their patterns), which may nonetheless be of considerable significance. The technique can be a useful preliminary exercise in assessing magnetic response and locating well defined and strongly magnetic features, but it should not be relied upon as the sole geophysical method used to evaluate an area. This applies also to variants of the method that log the instrument signal, using grid location and/or GPS navigation.

The latter is presently rarely practised and the reliability of output from all methods of scanning is difficult to assess. Advice on this may change as methods become more refined.

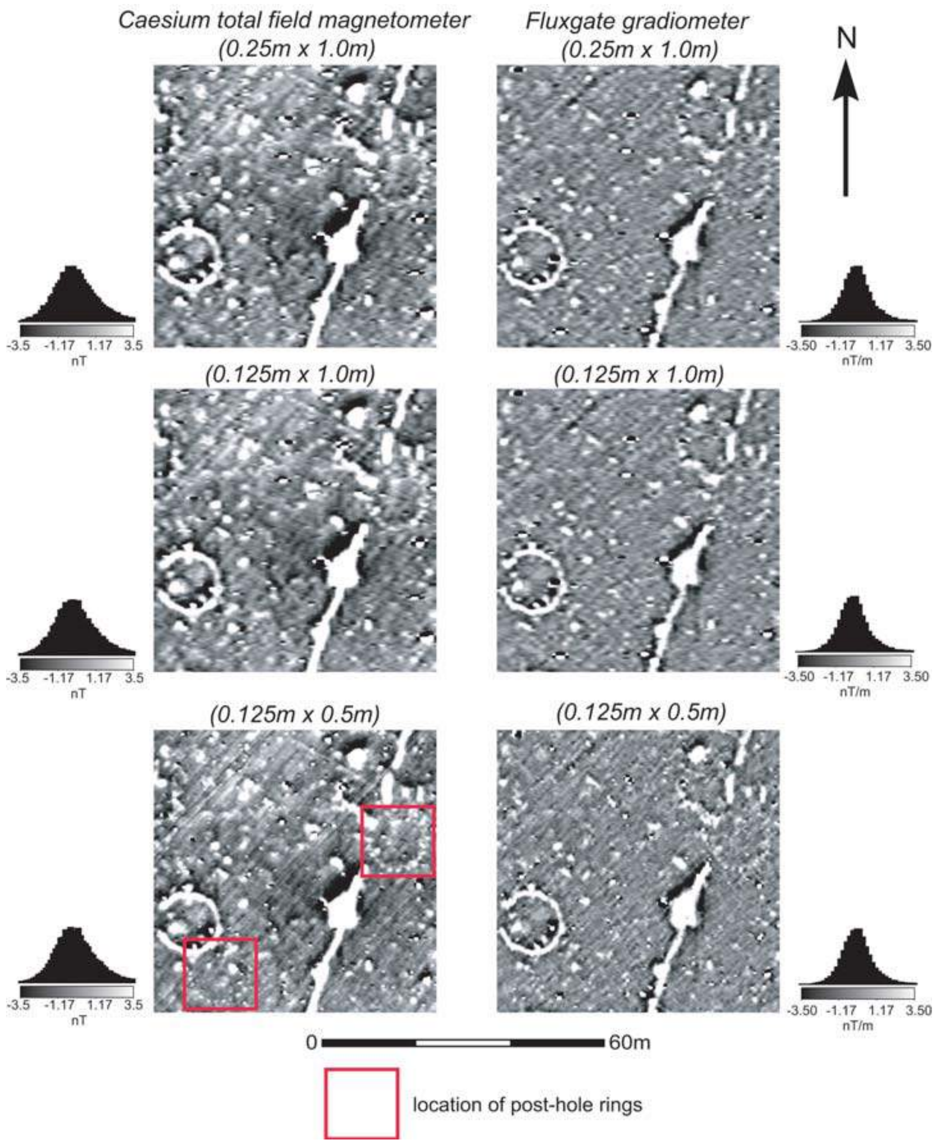



**Fig 6** (above) Caesium magnetometer and fluxgate gradiometer data collected at varying sample intervals, illustrating the effect of increasing traverse density for detecting discrete anomalies.

While most magnetometers now boast non-volatile storage capacities capable of storing more than a day's worth of surveying, it is advisable to transfer data frequently to a portable computer to avoid excessive data loss in the event of an instrument malfunction. Frequent checks of the data being collected are also advised to ensure that adverse site conditions or faulty instrumentation are not compromising quality. Surveyors need to be alerted to factors such as the incorrect balancing of the instrument and the possible presence of magnetic contamination on the operator, as both can significantly distort data. If the magnetometer is responding poorly to local conditions then adjustments to the survey procedure should be made to compensate for these. To guard against unexpected failure of the portable computer, data should also be backed up to a suitable secondary storage medium at the end of each day's surveying.

### *1.2.4 Units of magnetic measurement*

Magnetometers measure changes in the Earth's magnetic field and the SI unit of magnetic field strength is the tesla (T) (Moskowitz 1995; Payne 1981; Taylor 1995). However, this unit is inconveniently large with respect to the weak magnetic anomalies caused by archaeological anomalies, so magnetometer measurements are normally quoted in nanotesla (nT) where $1nT = 10^{-9}T$. Gradiometers measure the difference between two magnetic measurements separated by a fixed distance. Units of magnetic field gradient nT/m might be deemed appropriate, but a true gradient is only measured when the decay in magnetic field strength is linear between the two sensors and this is generally not the case unless the nearest causative features are at a distance much greater than the sensor separation. Hence, most magnetometer manufacturers simply quote the difference in nT between the measurements made by each of the two sensors and do not normalise for the sensor separation. It has thus become accepted practice in UK archaeological geophysics to quote gradiometer measurements in nT. However, where this convention is used, it is important that the sensor separation is also noted, as measurements made over the same anomaly will differ depending on the sensor separation of the gradiometer used.

## 1.3 Earth resistance (resistivity) survey

While research continues to produce many refinements to the electrical prospecting technique, for most field evaluations standard earth resistance survey is required. Details of theory and field procedures have been extensively aired in the literature (eg Clark 1996; Gaffney and Gater 2003) and instruction manuals (eg Walker 1991). Hence, the following guidelines do not aim to provide detailed theoretical or methodological information but simply set out to establish basic parameters of good practice.

### *1.3.1 Choice of earth resistance survey*

The rate of coverage using earth resistance survey is limited by the need to make direct electrical contact with the ground by the insertion of electrodes. A number of developments, such as mounting electrodes on a fixed frame as well as automated measurement and data recording have greatly increased the speed at which this can be done. Nevertheless, the rate of ground coverage typically remains about half that possible using a magnetometer, so survey costs per unit area are generally higher. It is thus particularly important that earth resistance survey is used economically and in circumstances suited to its particular strengths.

Earth resistance survey can often identify ditches and pits because they retain more (or sometimes less) moisture than the surrounding soil. However, in many instances the chances of detecting these with a magnetometer are higher and this more rapid technique should be preferred. Exceptions might be considered in areas of extreme magnetic interference or

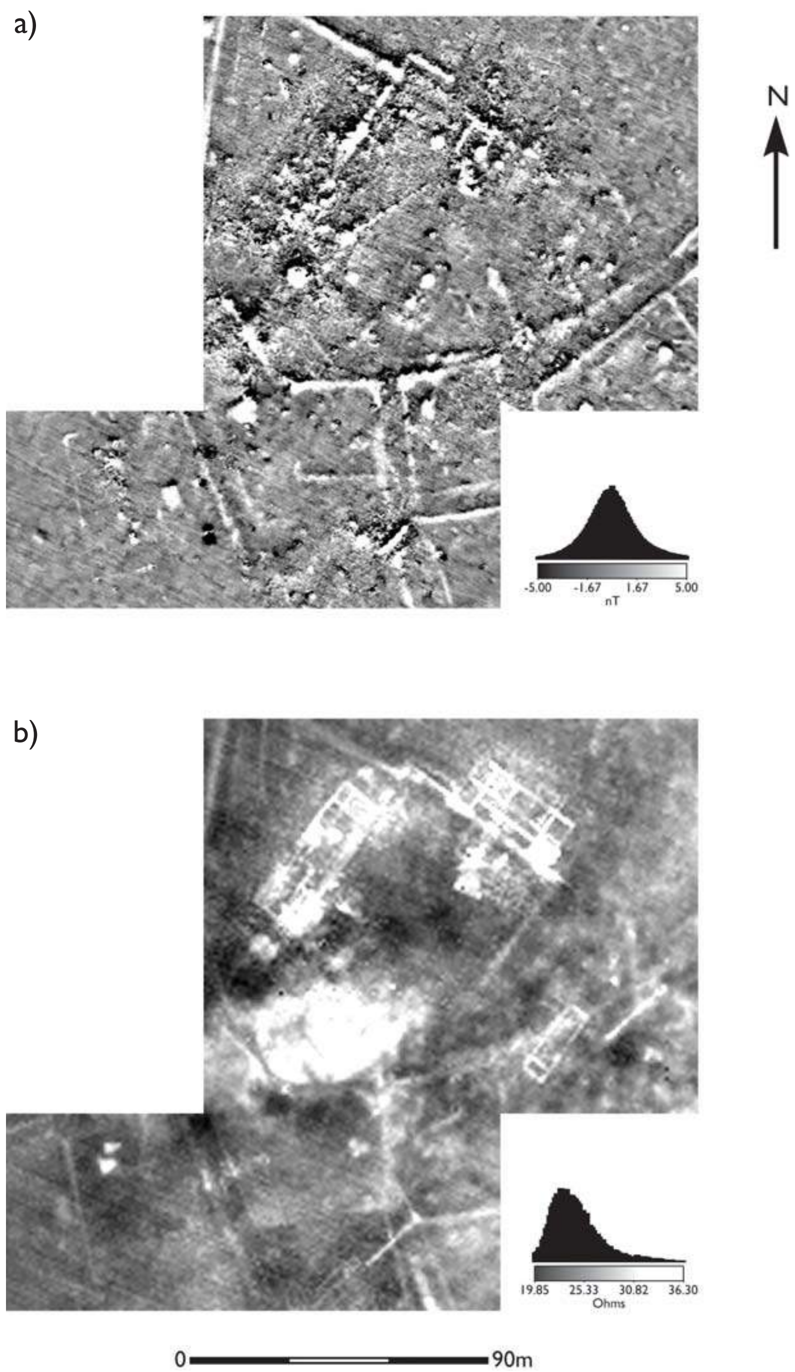



**Fig 7** (above) Caesium magnetometer (a) and earth resistance (b) survey of the same area of a Roman site in Hampshire. Both detect ditches but the earth resistance survey reveals wall footings in clear plan where the magnetometer survey shows just magnetic 'noise' from ceramic debris.

where soil and geological conditions are not conducive to the development of anthropogenic magnetic anomalies. Conversely, earth resistance survey should be favoured where building foundations and other masonry features are suspected, for instance over Roman villas, ecclesiastical and other medieval buildings, defensive works, etc. When applying earth resistance survey there should already be a strong presumption that such features exist within the survey area. In this sense, earth resistance is not a primary prospecting technique and its application in many evaluations will be secondary (Level II: Gaffney and Gater 2003, 88–91).

Magnetometer and earth resistance survey complement each other (Fig 7) and, for large evaluations, it is often best to assess the area magnetically first, followed by selected earth resistance survey of areas identified as likely to contain building remains. Choice of survey method is rarely so simplistic, however, and will depend upon a balanced expert consideration of each separate situation. Those who commission geophysical evaluation should ensure that the particular works proposed are adequately justified prior to the settlement of the contract. It is especially important to be certain whether or not earth resistance survey is appropriate.

### *1.3.2 Instrumentation*

While earlier resistance meters such as the Bradphys and Martin-Clark systems are still in use, they do not provide the pace of operation or data handling facilities of more modern instruments. The most commonly employed resistance meters for contemporary area surveys are listed in Table 6. These systems make measurements automatically when electrical contact is made with the ground and can automatically record readings to on-board electronic memory. The Geoscan RM15 system (Fig 8) is particularly versatile, with optional modular extensions creating a frame mounting up to six multiplexed electrodes. Under favourable conditions several measurements at different electrode separations may be made each time the frame contacts the ground; one application of this facility is to speed data acquisition by collecting two parallel traverses of data simultaneously. Recent innovations have allowed earth resistance meters to be used with cart-based platforms on which spiked wheels replace the traditional electrodes. These platforms offer faster rates of ground coverage and it is possible to mount other instruments, such as GPS receivers or magnetometers, for simultaneous coverage.

### *1.3.3 Methodology*

The type and standards of grid layout are the same as for magnetometer survey. For area evaluation surveys the twin electrode (or twin probe) configuration (Clark 1996, 38) will normally be employed. Using this configuration, the vast majority of buried features are detected as simple single-peaked anomalies, and anomaly shape is only weakly dependent on the orientation of the electrode array (Aspinall and Lynam 1970). Cart-based systems may, alternatively, use the square array, which has similar response characteristics but avoids the need for fixed remote electrodes. However, it should be noted that three different measurement configurations may be used with a square array (usually termed *alpha*, *beta* and *gamma*) and each is preferentially sensitive to anomalies running in a particular direction (Aspinall and Saunders 2005). Hence, it is recommended that both alpha and beta measurements are made over a survey area when using the square array.

Clark (1996, 57) considers optimum electrode separation for the detection of features buried at different depths. However, it is rare that the precise burial depth of archaeological features is known in advance and, for the twin electrode array, a mobile electrode separation of 0.5m is now standard and detects features up to 1m beneath the surface. Where deeper overburdens are expected, a separation of 1m is commonly employed. Electrode separations much greater than 1m tend to result in multiple-peaked anomalies and unacceptable loss of definition. Modern multiplexers and modular frames enable measurements at several different electrode

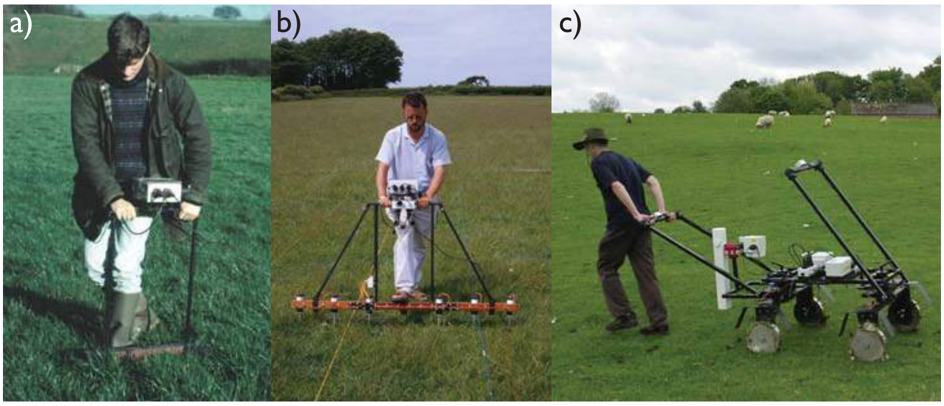



**Fig 8** (above) Geoscan RM15 earth resistance meter in use (a) in standard twin electrode configuration; (b) with a multi-electrode array addressed via an MPX15 multiplexer (photograph courtesy of Roger Walker, Geoscan Research Ltd); (c) mounted on an MSP40 square array cart with a fluxgate gradiometer also attached.

**Table 6** Earth resistance meters commonly used for UK archaeological surveys.

| *Manufacturer* | *Model* | *WWW URL* | *Type* |
|---|---|---|---|
| ABEM | Terrameter LUND imaging system | http://www.abem.se/products/sas4000/sas4000.php | 64 channel multiplexed system for electrical imaging surveys. |
| Campus | Tigre | http://www.campusinternational.co.uk/campus_tigre.html | 32, 64 or 128 channel multiplexed system for electrical imaging surveys. |
| Geoscan Research | RM15-D | http://www.geoscan-research.co.uk/page15.html | Lightweight meter for use with mobile electrode frame. MPX15 6 channel multiplexer available as addition. |
| TR Systems | Resistance Meter | http://www.trsystem.demon.co.uk/html/resistance_meter.html | Lightweight meter for use with mobile electrode frame. |

separations to be collected simultaneously. The combined results can provide a degree of vertical characterisation for buried features (Fig 9) or be used to filter out geological trends and accentuate near-surface archaeological features (Clark 1996, 155–6).

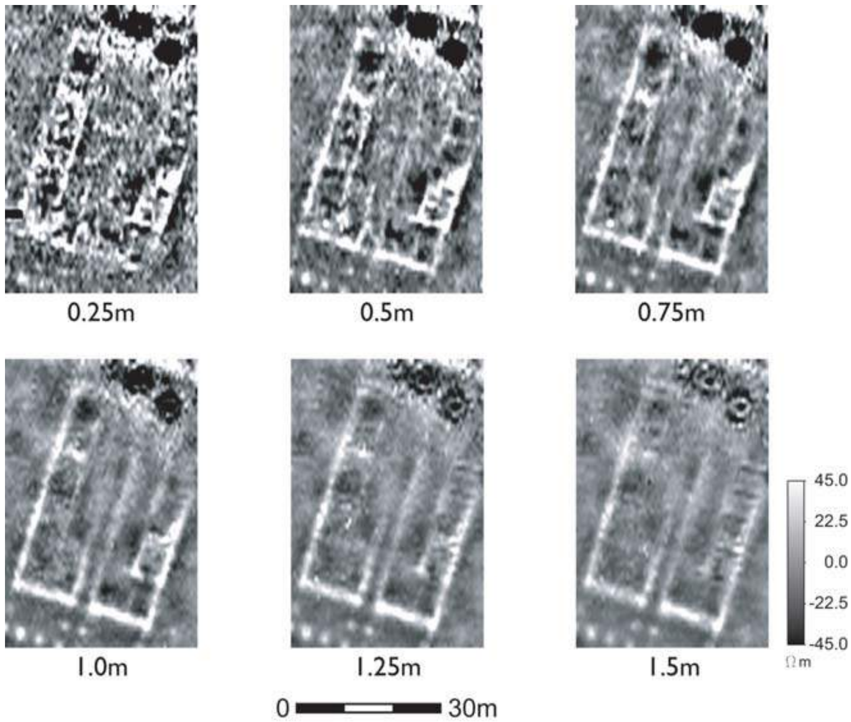
Different geologies, soils, and differences in soil moisture and chemical content can all affect the magnitude of the earth resistance anomaly caused by a buried feature; the optimum range setting and measurement resolution will therefore usually have to be determined for each site at the time of the survey. Under typical UK conditions measurements might range between 0 and 200 ohms in which case a resolution of 0.1 ohm would be suitable. However, in dry conditions much higher earth resistances can be encountered and a measurement range of 0 to 2000 ohms might be needed, in which case a resolution of 1 ohm would be acceptable.

The standard reading interval for earth resistance surveys in field evaluations is 1m × 1m, and this sample density should be adequate to detect the presence of archaeology in most circumstances. Increasing sample density to 0.5m × 1m or 0.5m × 0.5m can produce sharper detail (Fig 10) but increases the time required to survey the area (Clark 1996, 162) although modern multiplexed systems can minimise the additional time required. At the standard interval it should be possible to cover about 0.75 to 1ha per day.

Area survey with the twin electrode system involves positioning two fixed remote electrodes at a distance of some 15m to 30m (~30 times the mobile electrode separation) from the mobile frame and connected to it by a cable. As the survey progresses it will become necessary to reposition the remote electrodes so that the survey can continue and care should be taken to 'normalise' measurements between the new and old remote electrode positions to avoid discontinuities in the measured survey data (Gaffney and Gater 2003, 32–4). The need for normalisation may be greatly reduced, or even eliminated, by separating the remote electrodes from each other by a large distance (Dabas *et al* 2000) but at the expense of maintaining a greater separation from the mobile frame (necessitating a longer cable) and increased sensitivity to electrical interference. Underground electricity cables and pipelines with cathodic corrosion protection can produce significant electrical interference and, when working in their vicinity, care should be taken to set the resistance meter's current frequency filters and measurement averaging times to ensure that a stable measurement can be achieved. Indeed, it may not be possible to survey for up to several metres either side of such underground electricity cables and pipelines.

In nearly all circumstances area earth resistance surveys should be conducted rather than isolated traverses. The use of isolated search traverses, or widely spaced traverses, is only acceptable when attempting to trace known features, eg wall alignments, defences, ditches, roads, etc. However, using such traverses blind, in isolation from supporting data is not advised because they are difficult to interpret. Now that instrumentation enables relatively rapid collection of data there is little excuse for the 'key-hole' type of survey unless site conditions dictate it. Rather, the survey should be as extensive as resources and good sense permit, allowing a full appreciation of background conditions against which to interpret anomalous indications. Recent developments in cart-based systems suggest that, in future, earth resistance coverage of much larger areas may be practicable within relatively short timescales.

Surveyors and their clients should of course be aware that the resistivity response depends on moisture contrasts in the soil, and that these are in turn interdependent with climatic regime, vegetation, soil and feature type. For optimum results it is necessary to take these



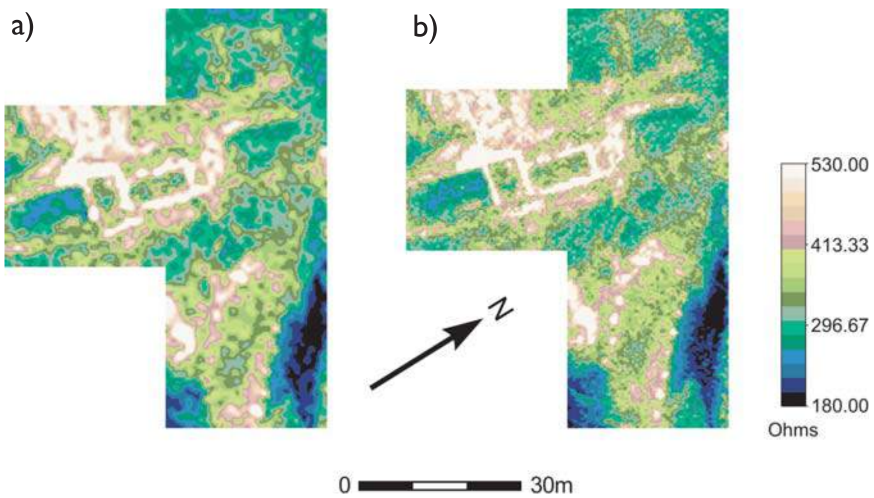




**Fig 9** (above top) Earth resistance survey conducted using six different electrode separations over a Roman building at Wroxeter, Shropshire. The closer separations detect near-surface features, such as the footings of internal partition walls, while the wider separations preferentially detect the footings of the external, structural walls indicating that these continue to a greater depth below the surface (data courtesy of Roger Walker, Geoscan Research Ltd).

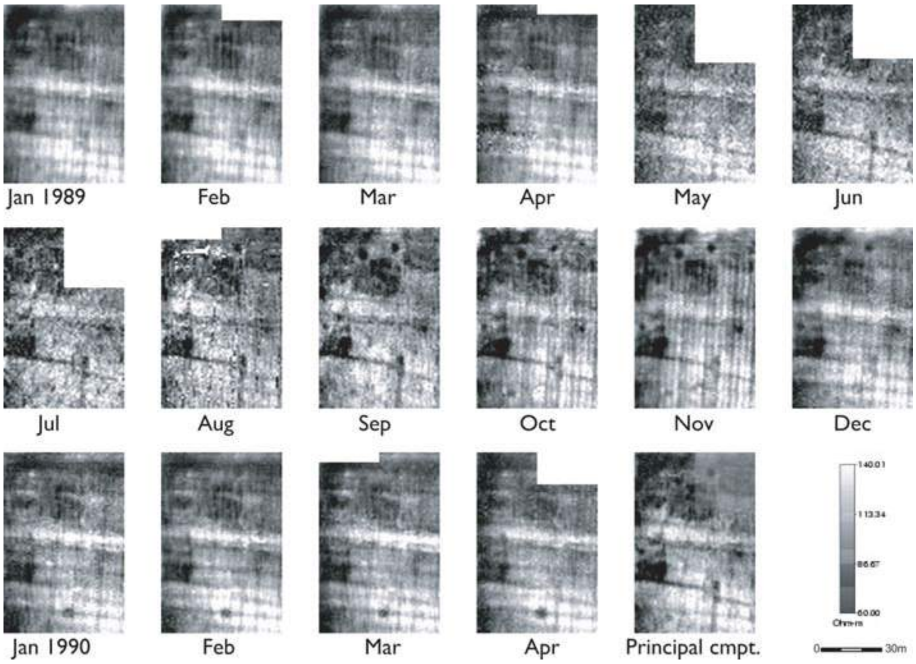
**Fig 10** (above bottom) Earth resistance surveys at Freens Court, Herefordshire, with readings at 1m × 1m sample density (a) and 0.5m × 0.5m density (b), illustrating the improved resolution of the latter, which resolves two rows of discrete post pad anomalies in the eastern (bottom) part of the survey area.

factors into account and, preferably, to conduct the survey at a time when moisture contrasts are at their most accentuated, or to resurvey the site at different times of year (Fig 11 and Clark 1996, 48–56). Regrettably, such approaches will be unrealistic within the time constraints of most development programmes and any such limitations should be noted in the subsequent report.

### *1.3.4 Electrical sections*

Earth resistance measurements are most sensitive to features buried at a particular depth, which, as mentioned above, is influenced by the electrode separation of the array used. By repeating measurements at each point on the surface using a number of different electrode separations it is possible to obtain rudimentary information about the variation of earth resistance with depth – a simple example using six different separations is illustrated in Fig 9. However, more detailed depth information may be determined by laying out a large linear array of electrodes (often 25 to 64) and connecting them to a multiplexed earth resistance meter with multi-core cables, so that measurements at all possible separations and positions are made (Milsom 2002, 114ff).

Each measurement uses four of the electrodes in the array, selected by the multiplexer and conforming to one of the standard electrode configurations (eg Wenner or dipole-dipole). By ascribing each measurement to a horizontal location beneath the centre position of the four electrodes used and a depth proportional to their relative separation, a vertical slice through the ground known as an electrical pseudo-section can be built up. Such pseudo-sections contain distortions resulting from the often complex interaction between the electric current flow and resistive anomalies in the subsurface (Aspinall and Crummett 1997), but a more accurate electrical section may be created using computer post-processing with iterative inversion algorithms (*see below*, section 2.1.3 and Loke and Barker 1996) – a technique often referred to as electrical imaging or tomography. An example showing the use of electrical imaging to characterise buried wall footings is shown in Fig 12.



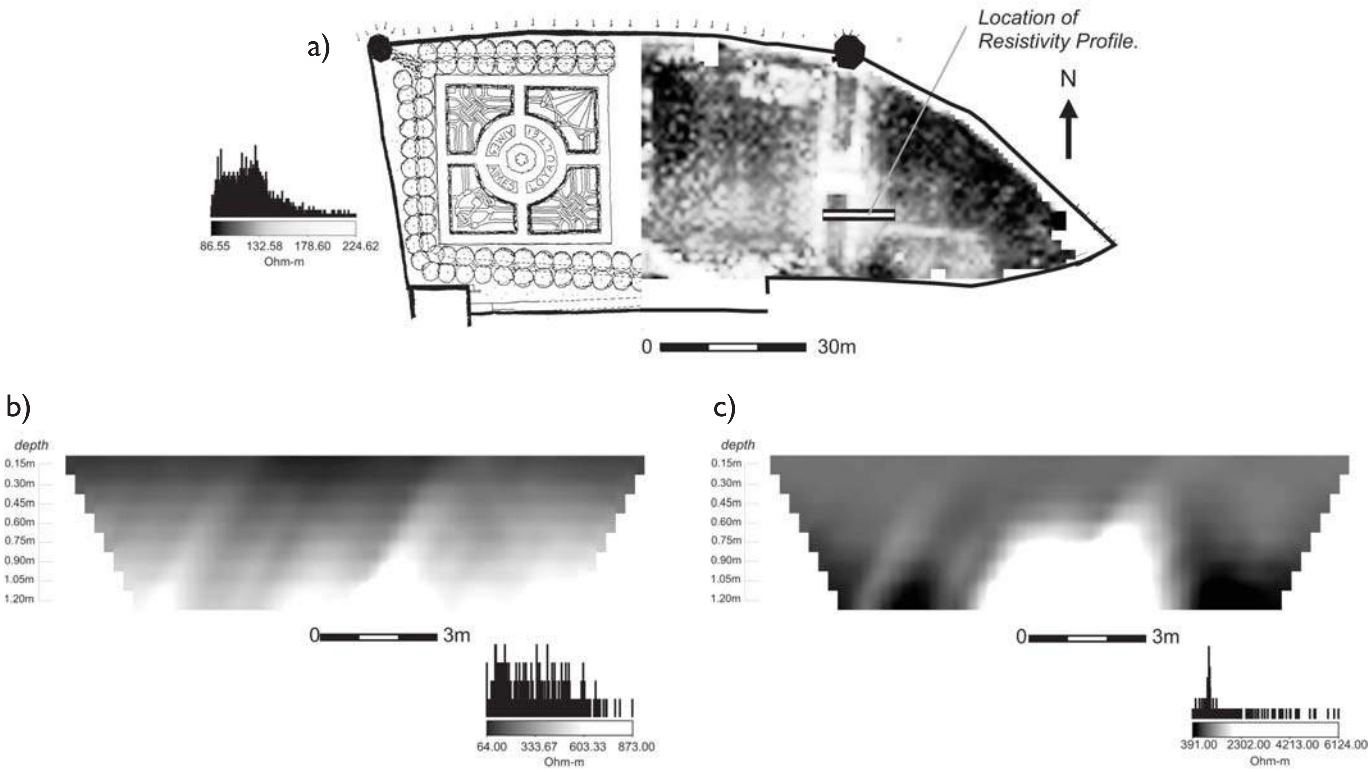




**Fig 11** (above top) Earth resistance surveys over the same area at Stanwick Roman Villa, Northamptonshire repeated at monthly intervals for eighteen months, illustrating the seasonality of the response of archaeological features to this technique. High resistance (white) anomalies are clearest in winter when the soil has a high moisture content, while low resistance (black) anomalies are clearest in the summer months, when there is a high soil moisture deficit.

**Fig 12** (above bottom) Earth resistance survey at Basing House, Hampshire: (a) 0.5m twin electrode earth resistance area survey identifying a portion of the medieval curtain wall footings (strong white linear anomalies); (b) pole-pole 'pseudo-section' showing the earth resistance of a vertical profile along the line indicated in (a); and (c) inversion of the data shown in (b) clearly showing the buried wall footing in cross section.

Electrical imaging has been employed with some success to characterise archaeological anomalies and three-dimensional surveys can be constructed by measuring a sequence of parallel sections and stacking the results (Collier *et al* 2003). However, the technique is slow compared to area survey methods, as a large number of electrodes need to be pre-positioned for each section. Electrical sections are therefore usually employed to improve the characterisation of anomalies rather than for their initial discovery. For this reason they have been little used in UK archaeological evaluation surveys and should only be considered when there is an agreed need to further characterise potential archaeological anomalies after initial discovery by area survey techniques.

Nevertheless, they are increasingly employed in geomorphological studies to provide details of buried landscapes associated with archaeological activity. In this application, large geological-scale sections are measured at strategically targeted locations, typically using more widely separated electrodes than for direct analysis of archaeological-scale anomalies (Bates and Bates 2000; Bates *et al* 2007).

Where electrical sections are employed, an inter-electrode spacing suited to the scale and depth of the expected anomalies should be chosen. This might be as narrow as 0.5–1m when imaging archaeological features, but may be much wider (2m, 5m or more) for geomorphological studies. Different electrode configurations (Wenner, dipole-dipole, etc) have different response characteristics (Loke 2004), so the configuration used and the reasons for its selection should be noted in the survey report. Care should also be taken to minimise the contact resistances of each electrode in the array (typically to <1000 ohms) before initiating the measurement sequence. Most data acquisition software for electrical sections will include a facility to test the contact resistances of each electrode and, where contact resistance is found to be unacceptably high, the insertion point can be moistened with water and the electrode re-inserted to improve the electrical contact.

## 1.4 Ground penetrating radar

Collectively, the term ground penetrating radar (GPR) has been applied at an administrative level within Europe to all methods of geophysical survey utilising electromagnetic radiation in a range from 30MHz to 12.4GHz to image buried structures. This encompasses a wide range of applications and the term is used here to describe the more common, commercially available GPR systems suitable for archaeological surveys (Conyers and Goodman 1997; Daniels 2004; Reynolds 1997; Vaughan 1986).

### *1.4.1 Choice of GPR survey*

GPR can often be more costly than conventional methods of area geophysical survey (eg magnetic and earth resistance techniques), but does present some unique capabilities to provide estimates of the depth to target features and, under suitable conditions, present three-dimensional models of buried remains. GPR can also be the only practical method to apply on certain sites, or within standing buildings, where the presence of hard surfaces and above-ground ferrous disturbance precludes the use of other geophysical techniques. However, the resolution of vertical stratigraphy is limited and highly dependent on both site conditions and the instrumentation deployed.

**Table 7** Summary of expected GPR response over various types of site and features.

| *Type of site or feature* | *Expected response* | *Comments* |
|---|---|---|
| building remains, foundations and wall footings | good | Generally very well resolved; previous earth resistance survey may indicate sufficient conductivity contrasts. |
| services | good | Modern services, particularly metal pipes, can be readily distinguished. Small bore plastic services may be more difficult to image. More significant stone-lined drains and conduits can also be resolved. |
| site stratigraphy | moderate | Providing adequate physical contrast between adjacent layers and features exists, stratigraphy can be resolved within the limits of spatial resolution for the antenna (Table 9). |
| voids and cavities | good | The contrast between air-filled voids and surrounding soil produces a strong reflection. Distinctive polarity reversals of the incident wave form may also be discerned. Partially filled voids containing rubble or water may also be resolved. |
| standing structures, historic buildings | good | Specific architectural questions, such as the presence of hidden void spaces within a wall, may be resolved. High frequency antennas are often required and are effective for locating metallic features. |
| wetlands | moderate/good | Response may be highly site-dependent and influenced by the presence of high-conductivity clays. Success has been reported for imaging targets in peat and below fresh water. |
| geomorphology | moderate/good | Lower-frequency antenna may be required in the presence of alluvial clays, but palaeochannels and other large scale features can still be located. The depth of overburden can also be mapped. |
| pits, ditches, post-holes | moderate | Site-dependent, but successful surveys demonstrate the suitability of GPR to these feature types. Physical contrast and feature size can limit detection. |
| graves | poor | Dependent on the nature of interment and depth of the feature; stone-lined coffins should provide a strong reflector. |

A wide range of site surfaces may be considered for GPR survey, including concrete, tarmac and even fresh water, although the technique is limited by the attenuation of the signal in conductive media. In practice, this will largely be determined by the concentration of clay and the moisture content of the soil at the site. Highly conductive media, such as metal objects or salt water will prove largely opaque to the GPR signal. Strong reflectors in the near-surface will also reduce the energy transmitted to immediately underlying targets and this may include the local water table (or other near-surface interface). Ferrous reinforcement bars in concrete are also readily imaged by GPR but their presence will not, necessarily, preclude the identification of underlying reflectors.

For normal ground-coupled antenna, good physical contact with the site surface is necessary to ensure adequate coupling of the radar energy with the soil. As far as possible, vegetation and any other surface obstructions should be removed from the site prior to the survey. High-frequency, air-launched horn antennas are designed to be operated from above the ground surface for civil engineering applications (eg road deck investigations), but do not have sufficient depth penetration for archaeological surveys. Air-launched antenna may prove useful for surveying delicate architectural features (eg plaster mouldings, wall paintings or mosaic pavements) when it is desirable to have no physical contact between the instrument and the surface under investigation.

Many site-specific variables must be considered when using GPR, but in general it will respond to a wide range of archaeological features (Table 7), and is often successful over sites where earth resistance survey has proved fruitful (eg presence of masonry walls, void spaces, etc). GPR is sensitive to the interface between differing materials and some target features produce highly distinctive GPR anomalies (eg hyperbolic responses from point reflectors). However, the identification of complex material properties, for example distinguishing either human or animal bone from the surrounding substrate, is considered to be beyond the capabilities of the technique under typical field conditions.

Precise depth estimation from GPR surveys is often difficult to achieve, yet is a critical process for the successful presentation of results. Unprocessed GPR data, expressed in terms of the time delay of returned reflections, can always be recalibrated in the light of additional information (eg trial excavation results) to present a more accurate physical depth estimate for other unexcavated targets.

While the use of GPR for detailed large area surveys (>1ha) has increased it is often applied as a complementary technique, following the acquisition of magnetic or earth resistance data, to target specific archaeological anomalies identified over a more limited area of the site. Care must be taken to ensure that GPR survey is appropriate to a site, particularly if it is the only technique to be applied. The proximity to sources of radio-frequency (RF) interference that may affect the data quality – such as mobile telephone transmitter base stations or the radio modem of an on-site differential GPS system – should be considered.

### *1.4.2 Instrumentation*

GPR systems utilise an electromagnetic source, generated by a transmitter antenna on the ground surface, and record the amplitude and time delay of any secondary reflections from buried structures. These secondary reflections are produced when the GPR pulse is incident upon any media with contrasting conductivity ($\sigma$) or (dielectric) permittivity ($\varepsilon$), or both, to the medium above. The magnetic permeability ($\mu$) of the sub-surface will also influence the propagation of a radar wave, but for most practical considerations it may be ignored. In general, the GPR response will be largely determined by the local variation of water content in the sub-surface. The maximum depth of penetration for a GPR is governed by a combination of signal scattering and attenuation within the subsurface, through the dissipation of radio-frequency energy as eddy currents within conductive media.

The majority of archaeological materials and soils are semi-transparent to the GPR signal and this is able to penetrate to some depth, creating a series of secondary reflections from buried objects distinguished by an increasing time delay. The resulting time-amplitude data is displayed as a two-dimensional profile with the X-axis indicating the horizontal location of the antenna on the ground surface and the Y-axis representing the increasing time delay (depth) from the initial impulse. While radar waves propagate more slowly in the ground than in the air, velocities are still extremely high and the receiver electronics must be capable of recording events separated by less than a nanosecond ($10^{-9}$s). The recorded delay represents the total time required for an incident pulse to travel from the transmitter to the target and then for the reflection to return to the receiver. This dual pathway is known as a *two-way travel time* and can be converted to provide the approximate depth of buried targets where an accurate estimate of the sub-surface velocity can be made.

GPR systems consist of an antenna unit housing the transmitter and receiver, an electronic control unit, a data console and a power supply. Different configurations of these components are offered by the major manufacturers and each may have advantages in particular survey conditions (Table 8; Fig 13).

*Antenna units* The GPR impulse covers a comparatively broad band of frequencies, usually defined by a nominal 'centre frequency'.

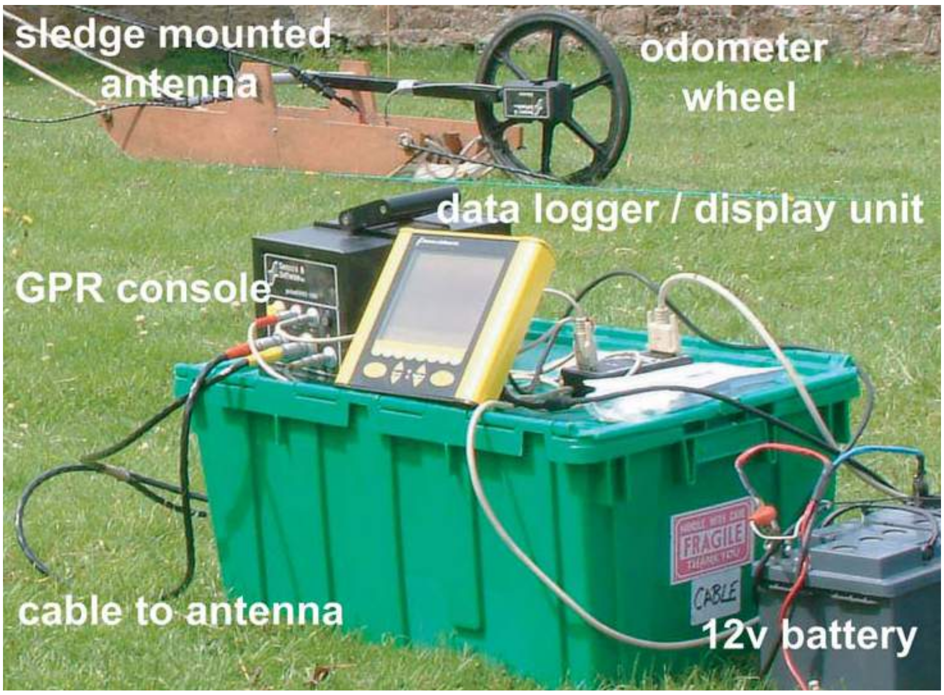



**Fig 13** (above) Annotated photograph of a Sensors and Software Pulse Ekko 1000 GPR system. The sledge accommodates either a 900 MHz, 450 MHz or 225MHz centre frequency antenna and maintains good coupling with the ground surface through its flexible plastic skid plate.

Because of the increased attenuation of higher frequencies, low-centre-frequency antennas will provide a greater depth of penetration. However, the longer wavelengths produced by low-centre-frequency antennas will reduce the vertical and lateral resolution of buried targets and only physically large structures will be resolved at depth (Table 9). The footprint of the subsurface illuminated by the approximately conical spreading of radar energy in the ground is also frequency-dependent and increases with depth (Annan and Cosway 1992, and Fig 14). This may limit the effective depth of investigation for certain targets and also introduce reflections from objects buried to either side of the instrument traverse.

The majority of commercial GPR systems allow operation with a number of interchangeable antenna units with different centre frequencies to suit the soil conditions, depth of penetration and resolution required. For near-surface archaeological surveys a bistatic antenna

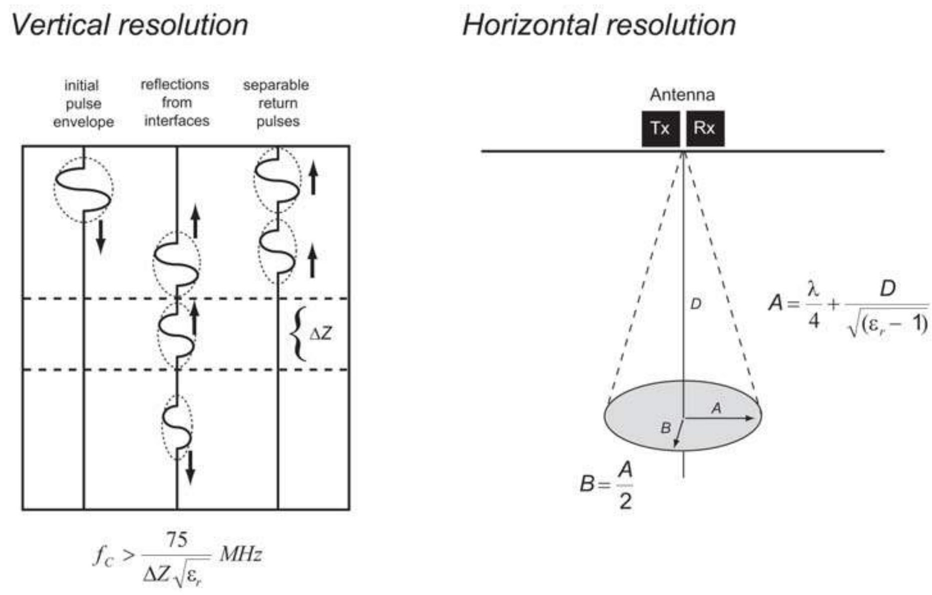



**Fig 14** (above) The vertical and horizontal resolution of a GPR can be estimated from the centre frequency of the antenna ($f_C$) and the relative permittivity ($\varepsilon_r$) of the ground from which the wavelength ($\lambda$) can be derived. The 'footprint' of the conically spreading energy increases with depth (*D*) reducing the effective horizontal resolution (figure adapted from Annan and Cosway 1992).

**Table 8** Manufacturers of current GPR equipment used for archaeological surveys.

| *Manufacturer* | *Models* | *WWW URL* | *Type* |
|---|---|---|---|
| ERA Technology | SPRscan | http://www.era.co.uk | cart-mounted system offering interchangeable 250, 500, 1000 and 2000 MHz antennas |
| GSSI | SIR, TerraVision | http://www.geophysical.com/ | systems offering a wide range of fully inter-changeable antennas from 40MHz to 2.2GHz options for cart mounting, borehole and multi-channel use. Multi-channel (14) 400MHz array (TerraVision) |
| IDS | RIS-ONE, RIS-PLUS | http://www.ids-spa.it/ | single- and multi- (8) channel systems using a range of interchangeable antennas from 80 to 2000MHz and also integrated multi-frequency units |
| MALA Geoscience | Ramac | http://www.malags.com/ | compact system with a range of fully inter-changeable antennas from 25, 50, 100, 200, 250, 500, 800MHz, 1.0, 1.2, 1.6GHz options for cart-mounting, borehole and multi-channel use |
| Sensors & Software | Pulse Ekko PRO, Noggin^Plus | http://www.sensoft.ca/ | systems offering a wide range of mainly separable antennas from 12.5, 25, 50, 100, 200, 250, 500, 1000MHz options for cart-mounting, borehole and multi-channel use. Noggin^Plus uses 250, 500 and 1000MHz antenna |
| 3d-Radar | GeoScope | http://www.3d-radar.com/ | digital stepped-frequency continuous wave radar system operating in a frequency range from 30MHz to 2GHz; multi-channel integrated antennas (1 to 63 channels) allow highly detailed data collection |
| Utsi electronics | GroundVue 1 to 5 | http://www.utsielectronics.co.uk/ | wide frequency range of twin-array beam focused antennas covering 30 – 100, 125 – 500, 200 – 600MHz, 1, 1.5 and 4GHz, cart-mounting, borehole, and multi-channel (4) use |
| Radar Systems Inc | Zond-12e | http://www.radsys.lv/ | dual channel GPR system with a range of ground-coupled antennas between 100, 300, 500, 900MHz, 1.5 and 2GHz; two air-launched antennas are also available operating at either a single frequency of 750MHz or a 38/75/150MHz combined unit |

unit, consisting of a separate transmitter and receiver will be used, although these may be enclosed within a common housing. Most mid- to high-centre-frequency antennas will also be shielded to minimise unwanted reflections.

More specialised antenna units designed for specific requirements such as borehole surveys or high-frequency air-launched systems for road pavement analysis are also available. Of greater interest to archaeological surveyors are multiple parallel antenna arrays, which allow rapid acquisition of densely sampled data-sets.

*Electronic control unit* These units provide the driving signal to the antenna and sample the received response at a sufficiently high frequency. Modern systems digitise the receiver data directly, enabling detailed post-acquisition processing. Some units may apply an analogue gain directly to the signal prior to digitisation, to improve the discrimination of later reflections, but it is important to avoid clipping the response beyond the maximum amplitude value recorded by the system. Older analogue instruments, producing only a graphical record of the GPR traces, are not appropriate for archaeological surveys because it is not possible to apply any post-acquisition processing or visualistion to the data.

Increasingly, GPR systems offer multi-channel operation where two or more sets of antennas can be recorded in a near-simultaneous manner. This might allow a site to be covered with a range of centre frequencies, imaging both near-surface and deeper-lying targets, or a parallel array of antenna units can be used for the rapid acquisition of densely sampled data.

*Data console* The function of the data console is to set the instrument parameters on the control unit, to view the receiver output in real time and to record the digitised data securely. A laptop computer running suitable control software can often suffice for this purpose, using an internal hard disk drive for data storage and a high speed transport bus to cope with the large volume of data produced by the GPR system. Integration with a co-located GPS receiver or robotic EDM enables the simultaneous collection of positional and topographic data (eg Leckebusch 2005).

*Power supply* GPR systems require a considerable power supply to function adequately throughout the working day. This power is usually supplied from a 12v lead acid battery but a direct supply may be possible from a vehicle mounted system. Lead acid batteries can pose a Health and Safety risk because of the weight of high power units and from potential liquid acid leakage. Gel acid batteries considerably reduce the risk of leakage.

*System mounting* More recently, integrated GPR systems have been designed for single user operation with all of the components mounted on a compact, collapsible wheeled cart. These systems are readily portable and may be deployed on more confined sites where the absence of trailing cables between the various subunits can greatly speed the rate of data acquisition. Transport of the antenna units may be improved by mounting these in a sledge with a flexible, plastic skid to ride over uneven terrain while maintaining good coupling with the ground surface. A GPR system may also include an odometer wheel to automatically trigger the unit at set distance intervals, although these may require calibration when operated over sites with uneven terrain.

### *1.4.3 Methodology*

This section considers only the use of impulse GPR operating in a *common offset* antenna configuration. Alternative applications of GPR are considered in section 1.7 below.

Initial field tests are recommended to confirm that the equipment is functioning properly, and that instrument parameters are correctly set. Antennas of differing centre frequencies should be trialled to determine an appropriate balance between resolution and depth of penetration (Fig 15). Operators should ensure that mobile telephones and any other RF transmitters in the immediate vicinity of an impulse GPR antenna are switched off. The survey may have to be conducted with more than one centre frequency of antenna, either because of rapidly changing site conditions (eg an increasing depth of overburden) or the need to resolve targets of differing physical size and depth of burial (eg on a deeply stratified urban site).

If the instrument trials prove unsuccessful, or suggest marginal data quality, then the survey should be aborted at a pre-agreed fee. This may be unnecessary for small surveys, where data acquisition is unlikely to exceed a single day in the field.

The requirement for the survey grid is similar to other geophysical techniques but operation on standing buildings may impose special requirements for recording the position of the antenna over the face of a wall or ceiling. Survey transects should, where possible, be positioned parallel to any surface irregularities, for example kerb stones, to maintain good antenna coupling with the ground surface. Strong radar reflectors (eg metal fences, walls or vehicles) present at the surface of the site may produce spurious reflections in the data caused by uncoupled energy leaking from the transmitter. This may occur over sites with uneven terrain where the antennas do not make good physical contact with the ground surface. Such *air wave* anomalies can be distinguished in the data as characteristicly high velocity (~0.3m/ns) and of limited attenuation compared with sub-surface reflectors.

**Table 9** Approximate values for the variation of GPR penetration depth and resolution with centre frequency for typical soils, encompassing a range of values for dielectric constant and soil conductivities. The horizontal resolution will decrease with depth and is given for the maximum penetration depth assuming a dielectric constant, $\varepsilon_r$ = 15. These values are intended as a guide and may be improved when a more detailed estimate of the site conditions and target parameters are available.

| *Centre Frequency (MHz)* | *Depth penetration for typical soils (m)* | *Wavelength ($\lambda$) in soil $\varepsilon_r$ = 15 (m)* | *Horizontal resolution –width of Fresnel zone at maximum depth (m)* | *Vertical resolution $\lambda$/4 (m)* |
|---|---|---|---|---|
| 1000 | ~1.0 | 0.08 | 0.2 | 0.02 |
| 500 | ~2.0 | 0.16 | 0.4 | 0.04 |
| 200 | ~3.0 | 0.39 | 0.8 | 0.10 |
| 100 | ~5.0 | 0.77 | 1.4 | 0.19 |
| 50 | ~7.0 | 1.55 | 2.4 | 0.39 |

Near-surface horizontal reflectors, such as concrete surfaces or metal manhole covers, may also cause the incident radar pulse to reverberate repeatedly between the antenna and the surface, resulting in high amplitude multiple reflections (ringing) down the profile.

There are three main modes of GPR data acquisition:

*(1) Scanning* GPR instruments provide a real-time visual display of the recorded data and may be used to locate known or suspected features, perhaps during invasive works in the field. Cart-based systems may be reversed along the survey line while scrolling the data backwards to identify the location of an anomaly.

*(2) Individual recorded profiles* Single profiles may be recorded over the suspected location of known features or to investigate anomalies identified by other geophysical techniques; for example, to estimate the depth to a particular target or to determine the course of a linear feature over an extensive area where the route may be interpolated between widely spaced traverses.

*(3) Detailed area survey* Area survey over a regular grid of closely spaced traverses is strongly recommended for detailed GPR investigations. Ideally, to avoid spatial aliasing, traverse spacing should be less than the approximate footprint of the radar energy at the required depth of investigation (Fig 14 and Table 9). Under typical conditions for a 500MHz centre-frequency antenna any traverse spacing above 0.25m will be spatially aliased. However, as such densely sampled surveys are difficult to achieve over large areas unless a multi-channel instrument is available, a traverse separation of 0.5m is suggested where spatial aliasing will not be detrimental to the interpretation of the target features. The non-symmetric radiation pattern from a GPR antenna causes the orientation of targets – with respect to the direction of the profile – to influence the anomaly produced. Repeat survey over orthogonal traverses, or very closely spaced parallel traverses (0.1m or finer) will improve the definition of features running closely parallel to the original orientation of the data profiles (eg Conyers 2004, 67). Profiles collected over a regular grid may be acquired in either a parallel or zigzag fashion, providing sufficient care is taken with the positioning of the antenna to avoid any offset between alternate lines.

The resulting high-density data are best presented as a series of *time slices* where each successive time slice represents the horizontal variation of reflector strength (energy) across the survey area for a given two-way travel time (or depth estimate). Visualising the GPR results in this format may greatly assist the interpretation of complex data-sets (although some types of anomaly, for example from dipping reflectors passing through several time slices, may not be adequately resolved). Additional modes of display and data analysis, including examination of the individual profiles, are also recommended. The use of false-perspective, three-dimensional representations of the data, such as cut-away solid models or iso-volumes, may enhance the visualisation of certain data-sets or anomalies, but should not be used as the sole method of visualisation (eg Leckebusch 2003; Linford 2004). Fig 16 provides examples of the various means of GPR data display.

The number of traces (scans) to be recorded along each profile, the time window through which reflections are measured for each trace and the number of times each trace is repeated at a particular sample point (stacking), should be set to appropriate values to image the targets under investigation. Because of the low signal-to-noise ratio of the GPR signal, over-sampling is recommended where this does not adversely slow data acquisition. For a typical archaeological survey, with a mid-centre-frequency antenna (500MHz), traces should be recorded at least every 0.05m along a profile. An increased trace density may be appropriate for more detailed survey with a higher-frequency antenna. Establishing the correct time window through field trials is, perhaps, more important as this will determine the maximum depth to which the GPR will record data.

Any time-to-depth estimate should be supported with details of how the sub-surface velocity was determined and applied to the data, taking into account any significant alteration of soil type across the site or variation in moisture conditions that may occur during the course of the survey. This may be achieved through either calibration between a recorded reflection and a known-depth target, analysis of the shapes of diffraction hyperbolas, common mid-point (CMP) measurements made in the field (Fig 17) or direct determination using time-domain reflectometry.

Most GPR acquisition assumes the profile is collected over a planar surface. Where significant topographic variation exists this should be recorded and an appropriate elevation correction applied to the GPR data. Under conditions of gently undulating terrain

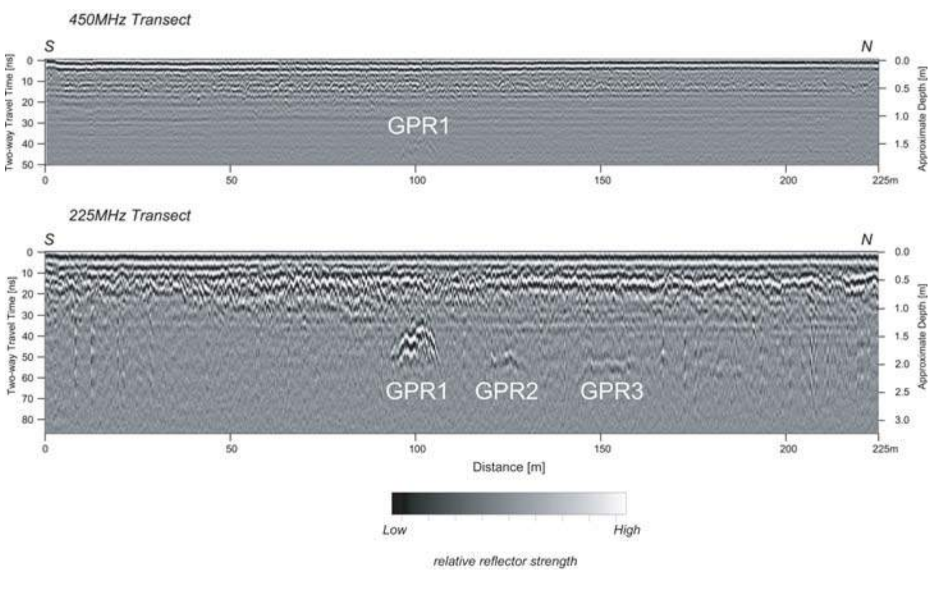
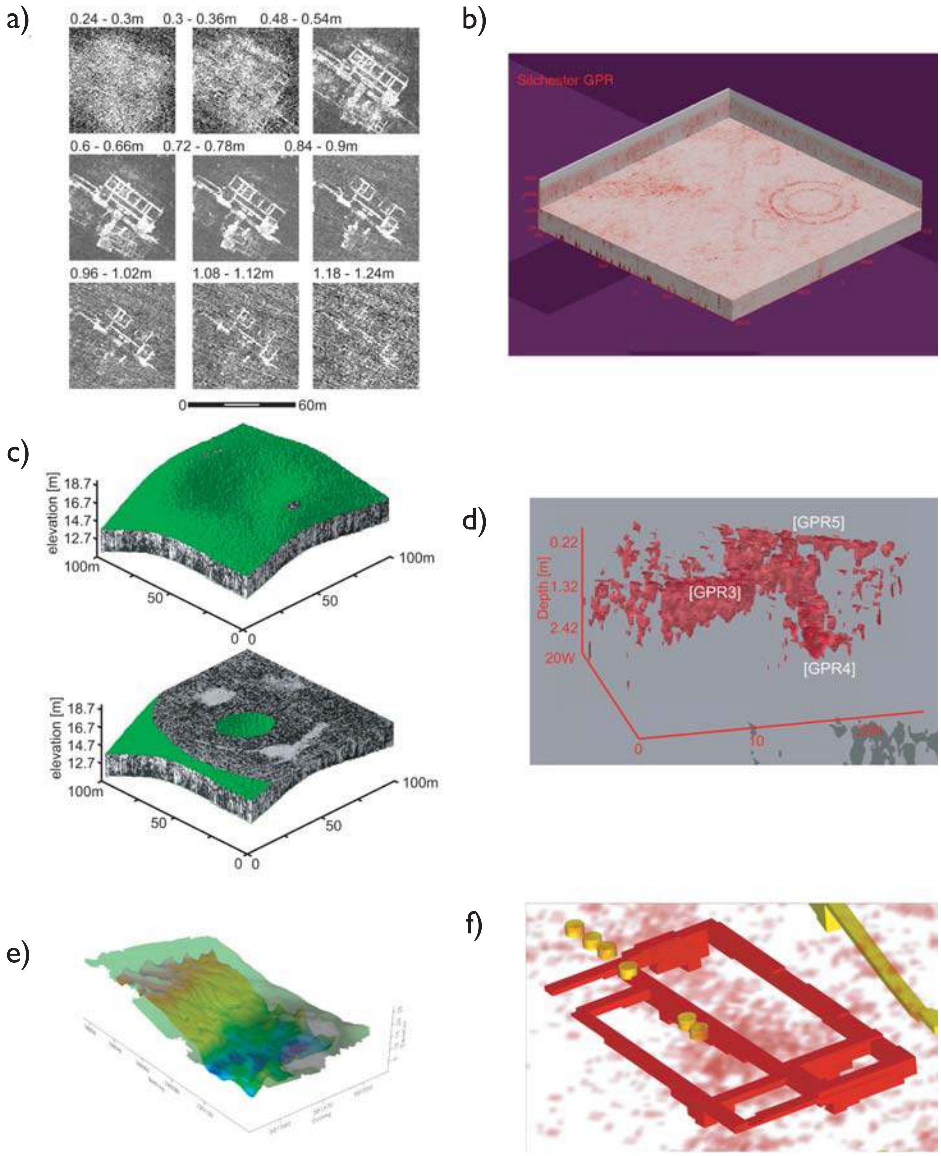
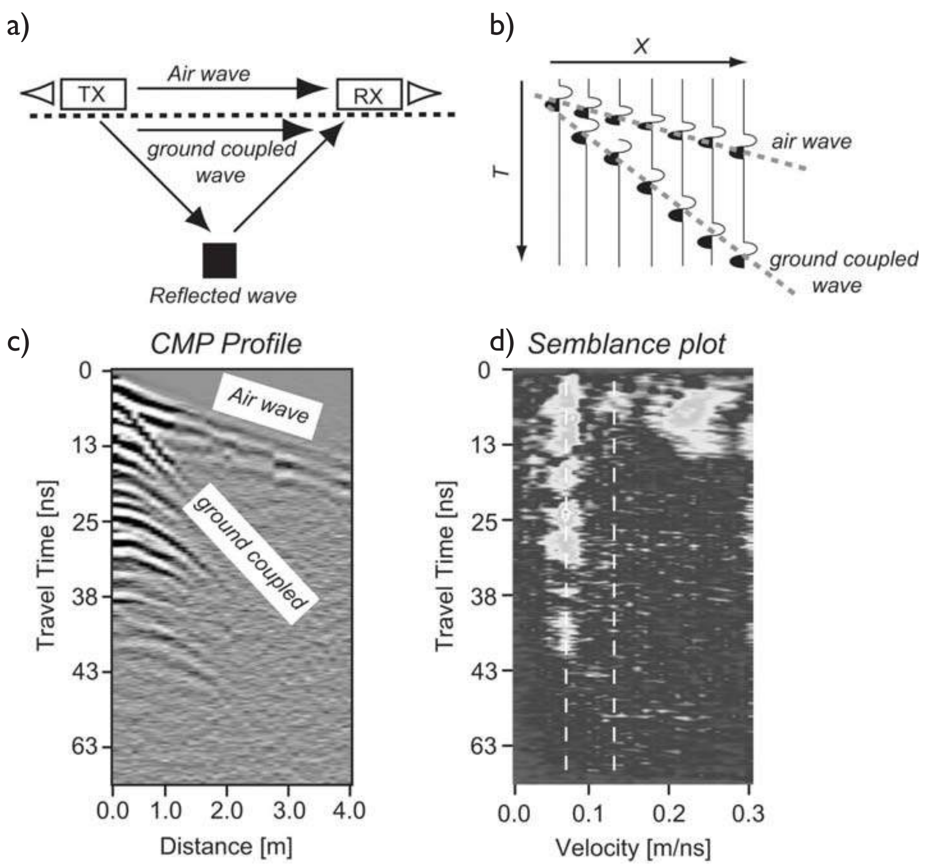



**Fig 15** (above) Trial GPR transect collected over peaty soil repeated with 450MHz (a) and 225MHz (b) centre frequency antennas. At this site the lower frequency antenna has successfully identified three deeply buried anomalies that are only partially represented in the higher frequency data.

**Fig 16** (opposite top) Examples of modes of display for three-dimensional GPR data: (a) time slices showing the variation of reflector amplitude at selected depths; (b) cut-away false perspective view of the whole data volume; (c) topographically corrected data volume showing underlying anomalies (greyscale); (d) iso-volume representation of stone-lined passages leading in to a souterrain feature; (e) buried land surface across a dry valley extracted from the GPR data beneath the (semi-transparent) DTM; and (f) a volumetric interpretation of a Roman building abstracted from time slice data overlaid with a cloud of plough damaged material.

**Fig 17** (opposite bottom) An estimate of the average subsurface velocity (*v*) can be obtained by conducting a common mid-point (CMP) survey in the field. (a) The distance (*X*), between the GPR transmitter and receiver is gradually enlarged about a central point increasing (b) the travel time (*T*) of both the air wave passing directly between the two and the ground coupled wave travelling through the very near surface, and any reflections, if present, from more deeply buried objects. The velocity of the waves can be determined from (c) the slope of the reflections on a CMP profile, which can be further enhanced by the use of (d) semblance analysis. In this case the velocity of the reflected waves from buried objects is approximately 0.075m/ns, slightly lower than the ground coupled wave (~0.125m/ns).




(within ±0.5m) the elevation correction may be applied directly to the GPR profile as a static shift to each trace. However, more severe gradients will also require a tilt-angle correction to be applied to the data to avoid discrepancies in the apparent location of subsurface reflectors (eg Goodman *et al* 2006; Leckebusch and Rychener 2007). The degree of horizontal displacement will depend on the slope angle of the surface and the depth of investigation. For example, anomalies identified at a depth of 1m below a slope inclined by 20° will be shifted horizontally by approximately 0.34m from the surface location of the GPR antenna.

Detailed GPR survey will create large volumes of data that will initially be stored on the internal hard disk of the data console or laptop computer. However, data back-up at regular intervals to suitable high-volume secondary storage media is recommended.

Results from a GPR survey, whether visualised as an individual profile or as a horizontal time slice, should indicate the time delay and include an appropriate greyscale or colour key to show the variation in the amplitude of the reflections. The recommended sub-unit for the two-way travel time delay is the nanosecond (ns) and the amplitude of the reflections will initially be recorded as a potential measured by the receiver antenna in the millivolt range, although results following post-acquisition processing are generally presented in arbitrary, relative units.

### *1.4.4 Radio licensing and emissions legislation*

Owing to the increased demand for wireless communications and the need to avoid interference between electronic equipment, legislation governing the use of the radio spectrum and electromagnetic compatibility (EMC) issues has been introduced and further regulations are currently under development at both a national and international level. GPR equipment must, obviously, adhere to the relevant legislation, but presents some unique considerations that do not readily fall into common categories of other similar electronic devices, such as cellular telephones or computer equipment.

Impulse GPR systems use a mobile, ultra-wide band (UWB) transmitter operating at a low-power output that is specifically designed to emit this energy into an absorptive earth-material medium, typically the ground. For archaeological applications of GPR this radiated energy generally falls between 30MHz and 12.4GHz, a portion of the radio spectrum that for administrative purposes is currently subject to legislation at a European level through standards set by the *technical authority* of the European Telecommunications Standards Institute (ETSI). The use of GPR equipment meeting the ETSI standard has traditionally been controlled at a national level but will be harmonised by the Europe-wide *regulatory authority*, the European Conference of Postal and Telecommunications Administrations (CEPT).

The use of GPR equipment within the UK must conform to all current radio licensing and EMC requirements. A formal licensing scheme for the UK was introduced by Ofcom from 1 September 2006 to regularise the situation existing under the previous waiver granted to members of the EuroGPR Association. From this date lawful operation of GPR equipment in the UK can only be achieved within the terms of the Ofcom licence, which requires full compliance with the EuroGPR code of practice, including the use of a site log for operation (see www.eurogpr.org and www.ofcom.org.uk for more details). Equipment rental pools will record site log details and licensing arrangements for occasional users hiring GPR instruments. These arrangements will, eventually, be superseded by wider European regulations following the recommendations of CEPT informed by a public enquiry period that closed in September 2006. The production of draft regulation by CEPT is currently ongoing, although some important technical issues, requiring the harmonisation of ETSI standards with regulatory decisions, are still to be resolved.

Generally, the areas of most concern are:

- airfields
- prisons
- defence establishments, including military training grounds
- radio astronomy sites

Most recently manufactured GPR equipment will have been designed to meet current EMC legislation and operate at a lower power than previous comparable instruments. These requirements also permit the operation of wide-band pulse techniques following the current entry in the UK Frequency Allocation Table on a non-interference basis between 150 and 4000 MHz, excluding the use of certain antennas at both ends of this range. Advances in antenna design and integral electronics often result in these modern systems surpassing the performance, in terms of depth penetration and signal-to-noise ratio, of the earlier generation of instruments that they have replaced (eg Sirri *et al* 2005). However, there are some applications where the original, high voltage, transmitters would provide the only means to obtain sufficient energy for imaging deeply buried targets in highly absorptive media. Additional concerns for the GPR user community are:

- operation beyond the agreed bandwidth (150 and 4000 MHz for the UK Frequency Allocation Table);
- compliance of older legacy equipment with new regulations;
- restrictions on the development of future equipment; and
- transmission surveys / vertical faces (control of energy absorption).

### 1.5 Electromagnetic methods

A range of geophysical instruments make use of electromagnetic (EM) waves, distinguished by the frequency and duration of the source

**Table 10** Manufacturers of current EM equipment used for archaeological surveys.

| *Manufacturer* | *Models* | *WWW URL* | *Type* |
|---|---|---|---|
| CF Instruments | CM-031 | http://www.allied-associates.co.uk/files/cm31.html | Similar to the Geonics EM31, the CM-301 has a 3.74m coil separation and operates at a frequency of 9.766kHz. |
| Dualem | various | http://www.dualem.com | A range of complete instruments and individual sensors is available, operating at a frequency of 9kHz that allows the simultaneous measurement of conductivity and magnetic susceptibility from two coil orientations; also coil separations of 1, 2 or 4m are available with some multiple spacing instruments for depth sounding. |
| Geonics | EM38, EM31 | http://www.geonics.com/ | The EM38 has a 1m coil separation for near-surface surveys and operates at a fixed frequency of 14.6kHz. Two variants of the basic instrument are also available offering simultaneous measurement of either both field components (EM38B) or coil orientations (EM38DD).<br>The EM31 has a coil separation of 3.66m and operates at a frequency of 9.8kHz, providing a depth of investigation to 6m. A 2m coil separation is also available (EM31-SH) for intermediate depths up to 4m. |
| Geophex | GEM-2 | http://www.geophex.com/ | The GEM-2 is a multi-frequency instrument operating over a range of 300 Hz to 96 kHz with a coplanar coil configuration separated by 1.66m. Geophex also manufacture a gradiometer EM system (GEM-5) designed for increased immunity to ambient environmental EM noise. |
| GSSI | EMP-400 | http://www.geophysical.com/ | The EMP-400 records 3 user selected frequencies simultaneously from a range between 1 to 16kHz and has a coil separation of 1.219m. |

that they utilise. While such a broad definition should include GPR, magnetic susceptibility meters and metal detectors, these special cases are considered individually elsewhere. This section therefore considers only inductive EM instruments, also known as 'slingram' or conductivity meters (Table 10). These emit a continuous low-frequency (<300 kHz) EM signal from a transmitter coil, that will in turn generate a secondary field within any electrical conductors present in the near-surface (eg Wait 1955). A separate tuned receiver coil records the modulated signal, where it is found that the in-phase component is proportional to the magnetic properties of the subsurface and the out of phase, or quadrature, response to the electrical conductivity. Theoretically, as conductivity is the reciprocal of resistivity, this modulated signal enables an EM instrument to simultaneously collect data-sets comparable to both the earth resistance and the (induced) magnetic response (eg fluxgate gradiometer survey) from a site.

While initial research demonstrated the ability of EM instruments to identify archaeological features (eg Scollar 1962; Tabbagh 1986; Tite and Mullins 1969), the technique is not, at present, widely used in the UK for archaeological evaluation. In principle, as the coils of an EM instrument do not necessarily have to make contact with the ground surface they offer the advantage of rapid field data acquisition, combined with the simultaneous collection of magnetic and conductivity data-sets. However, considerable inter-site variability of the EM response may be encountered, depending on underlying geology and soils, requiring calibration against more conventional methods of geophysical survey. EM instruments are also sensitive to conductive objects in the near-surface that may preclude their use, for example metal fences, rubbish, buried pipes, etc, and to electrical interference from both cultural (eg power lines) and atmospheric sources.

For most archaeological applications an EM instrument with an inter-coil spacing of approximately 1m will suffice, collecting data at a reading interval of 1m x 1m (Fig 18). Field operation and calibration will vary between instruments, but it should be possible to convert the recorded signal (often expressed as parts per thousand or ppt) to units of apparent conductivity in millisiemens per metre (mS/m) and volume magnetic susceptibility (dimensionless). The effective depth of penetration is largely dependent on the separation between the transmitter and receiver, analogous to expanding the electrodes of an earth resistance array, although the physical orientation of the coils allows even a fixed spacing instrument to provide a shallow (horizontal)

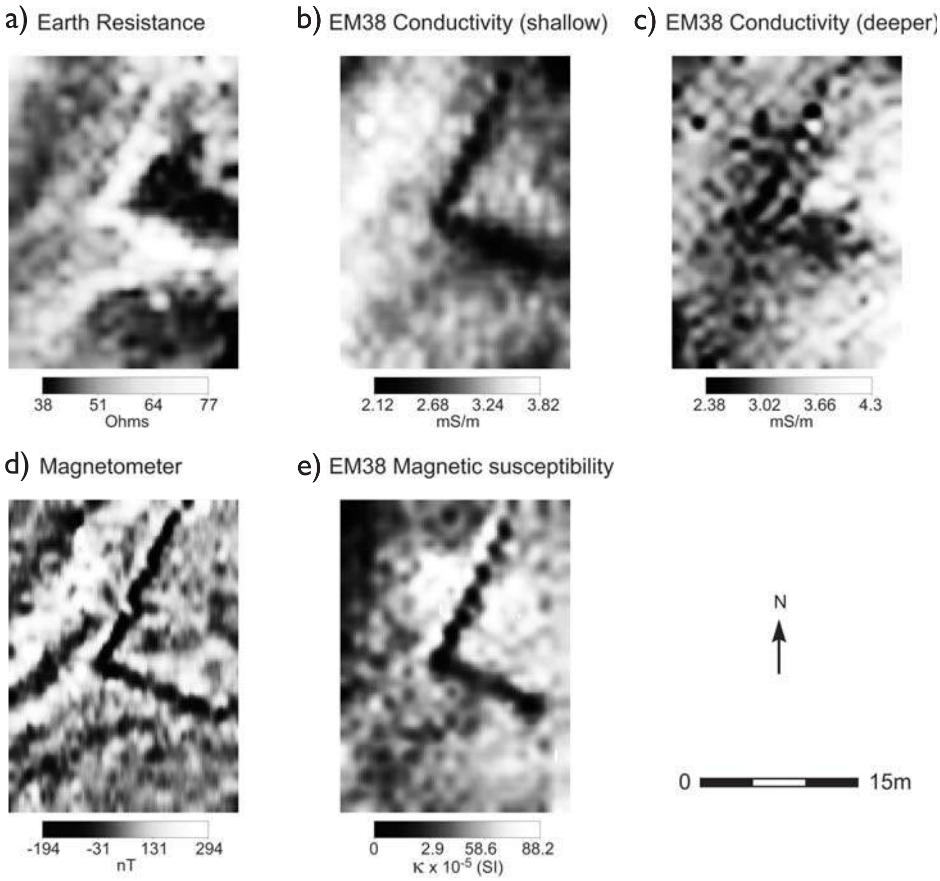




**Fig 18** (above top) Compact EM instruments with an inter-coil spacing of c 1m are well suited to archaeological surveys: (a) hand operated Geonics EM38B (14.6kHz) with integrated GPS recording both conductivity and magnetic properties of the subsurface; (b) single channel analogue EM38 mounted in a sledge; (c) Deeper penetrating Geonics EM31 (9.8kHz) with a 3m coil separation mounted onboard the GEEP multi-instrument sledge system together with two towed EM38s (photograph courtesy Ian Hill, University of Leicester).

**Fig 19** (above bottom) Comparison over a buried Roman wall between twin electrode earth resistance data collected with a 0.5m mobile electrode spacing (a) and conductivity data collected with a Geonics EM38 in shallow (horizontal) (b) and deeper penetrating (vertical) (c) coil orientations. Fluxgate magnetometer (d) and in-phase, vertical coil orientation, EM magnetic susceptibility data (e) over the same area are also shown.

and a deeper penetrating (vertical coil orientation) mode of operation (eg Keller and Frischknecht 1966). The frequency of operation will also influence the penetration depth and response of the instrument, depending on site conditions. Comparative studies with instruments such as the Geonics EM38 demonstrate a good correlation with twin probe earth resistance and magnetic surveys (Fig 19; Cole *et al* 1995; Huang and Won 2000; Kvamme 2003). However, certain combinations of site conditions, coil orientation, operating frequency and phase may produce a complex signal that is not directly proportional to a single physical property of the sub-surface (eg Linford 1998; Tabbagh 1986; Tite and Mullins 1973).

More widely spaced traverses may be of use when a deeper penetrating (wider coil separation) instrument is used to identify geomorphological features, such as palaeochannels, or map changes of soil magnetic susceptibility across an expansive landscape. Rates of coverage will vary depending on the precise instrument and sample interval in use, but should be similar to earth resistance covering approximately 1ha per day for a 1m × 1m sample interval survey. Vehicle-mounted instruments with integrated GPS measurements are more rapid and enable several hectares to be covered in a day at a coarse sample interval (eg 10m × 10m).

## 1.6 Topsoil magnetic susceptibility survey

Archaeological settlement activity often results in a localised concentration of soils and sediments with an enhanced magnetic susceptibility, because of the alteration of naturally occurring iron minerals (Clark 1983; Clark 1996; Cole *et al* 1995; Dalan and Banerjee 1998; Evans and Heller 2003; Fassbinder and Stanjek 1993; Linford 2005; Thompson and Oldfield 1986). Measurements are generally made in the field (although soil samples may be recovered for laboratory determination) at a coarse sample interval of 10m, utilising suitable instrumentation (Figs 20 and 21; Table 11). Care must be taken to account for the presence of masking deposits, the influence of recent land use and field conditions at the time of the survey that may reduce the contact between a field coil and the ground surface. Laboratory determination may make possible more detailed sample preparation and additional measurements (eg frequency dependence of susceptibility or fractional conversion). Units of volume specific magnetic susceptibility ($\kappa$) used for measurements made with a field loop are dimensionless within the SI system and laboratory determination from recovered soil samples should be corrected to values of mass specific magnetic susceptibility ($\chi$) in dimensions of $m^3kg^{-1}$.

Usually, a wider survey extending beyond the evaluation study area should be considered, to allow any regional correlation between magnetic susceptibility with geology and soil type to be distinguished from possible anthropogenic enhancement (eg Dearing *et al* 1996, fig 1).

Even under ideal field conditions topsoil magnetic susceptibility survey remains an indicative technique that is unable to establish the definitive presence, or absence, of archaeological remains without the support of additional methods of evaluation. Topsoil magnetic susceptibility survey alone is, therefore, not recommended and evidence of an indifferent response to this technique should not be used to discount the potential presence of archaeological features. The comparatively greater influence of ground surface conditions and masking deposits such as alluvium create anomalous areas of both increased and depleted topsoil magnetic susceptibility and should therefore always be investigated through subsequent detailed magnetometer survey.

Careful consideration should always be given to the benefits of total coverage by detailed magnetometer survey, as the enhanced level of interpretation drawn from the results may often outweigh the increased costs involved. However, topsoil magnetic susceptibility results are considered to be of value when either interpreting magnetometer data (eg Fig 20), or when assessing the suitability of varying soil types and geology in advance of conducting a detailed survey. Topsoil susceptibility measurements over stripped excavation surfaces and sectioned features have also proved to be useful at an intra-site level (eg Bayley *et al* 2001, fig 5; Linford 2003; Linford and Welch 2004), and borehole

**Table 11** Manufacturers of current magnetic susceptibility equipment used for archaeological surveys.

| *Manufacturer* | *Models* | *WWW URL* | *Type* |
|---|---|---|---|
| Bartington Instruments | MS-2 | http://www.bartington.co.uk/ | a highly versatile, portable magnetic susceptibility meter, offering dual frequency operation (0.465 and 4.65kHz), and a range of field and laboratory sensor coils. |
| Geofyzika | MFK1 Kappabridge | http://www.agico.com/ | various models of high sensitivity laboratory instrumentation operating over a range of frequencies (0.976, 3.904 and 15.616 kHz) |
| SatisGeo | KT-6 Kappameter | http://www.satisgeo.com/ | integrated hand-held sensor and meter operating at a single frequency of 10kHz with a penetration depth of ~20mm |
| ZH Instruments | SM-30, SM-400 | http://www.giscogeo.com/pages/maggysm2.html<br>http://www.heritagegeophysics.com/Magnetic_Susceptibility/SM-30_SM-100.htm<br>http://www.gfinstruments.cz/<br>http://www.zhinstruments.cz/ | The SM-30 is a compact hand held sensor and meter operating at 8kHz with a penetration depth of ~20mm. An automated borehole measurement system SM-400 is also available. |
| Geo Instruments | GMS-2 | http://www.fugroinstruments.com/html/inst/prod_magsus.htm | compact hand-held sensor and meter operating at 0.76kHz |

measurements have been used to successfully determine significant anomalies beneath surface deposits across wider landscapes (eg Dalan and Banerjee 1996).

## 1.7 Other geophysical methods

Despite offering limited use for traditional applications of archaeological evaluation a wide range of additional geophysical techniques is available that may, under certain conditions, be applicable. Some of the techniques discussed in this section are highly specific – for example the use of micro-gravity for the detection of buried voids – while other techniques propose new means for obtaining data-sets comparable with more traditional methods. Most of these latter techniques are currently at a stage of development between research and full commercial deployment, but may well be adopted as the technology matures in the near future.

### *1.7.1 Capacitative arrays*

These systems are designed for the rapid acquisition of apparent resistivity data and use a series of electrodes mounted on individual insulating mats that may be towed rapidly across a site without the need to obtain a direct contact with the ground surface. The electric potential produced by the charges on the electrodes causes the movement of charged particles in the ground resulting in a brief capacitative coupling, continuing only until an equal and opposite reverse potential has been established in the subsurface. Use of a sufficiently high frequency source will reverse the flow of charged particles in the ground, producing an alternating current in the subsurface. Similar dipolar pairs of insulated electrodes are then used to measure the potential created by the ground current.

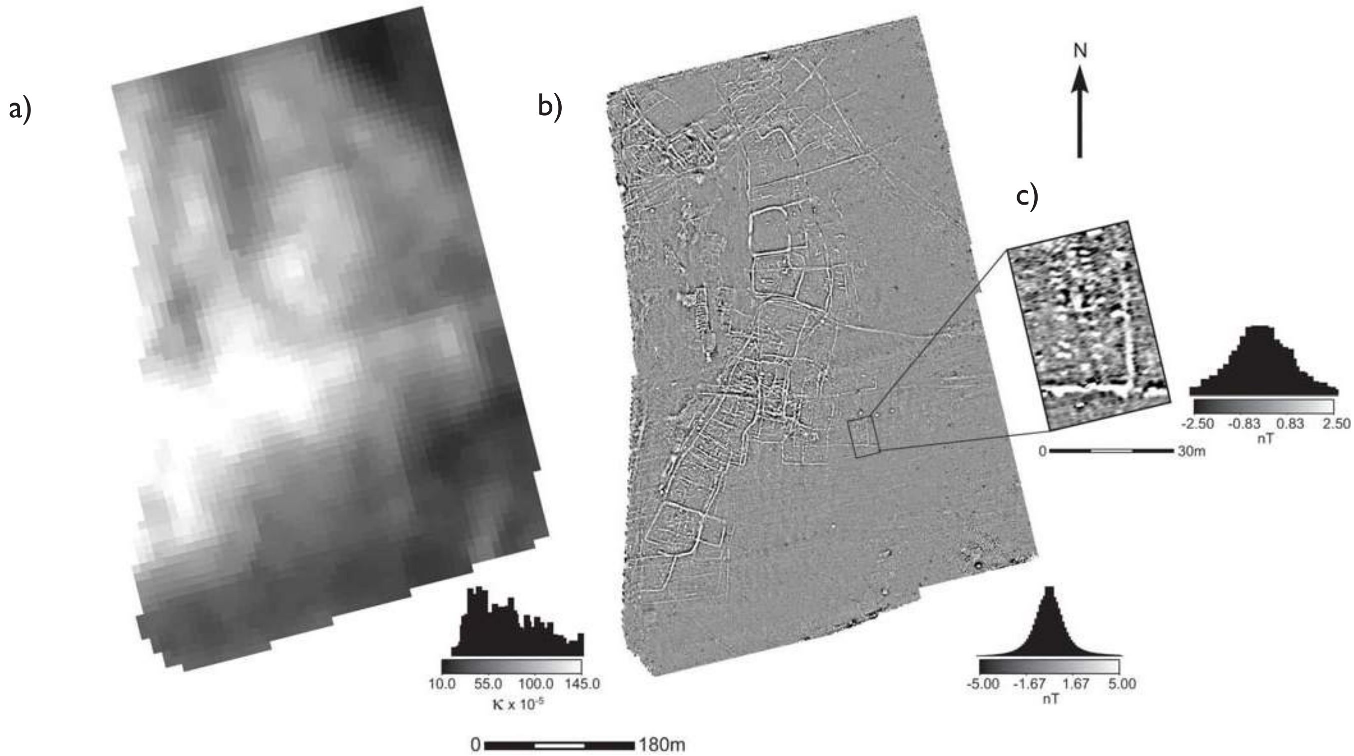
Multiple potential electrodes can be towed at different spacings behind the current electrodes to simultaneously measure the apparent resistivity at varying depths and can be inverted to provide a pseudo-section of the ground surface (*see above*, section 1.3.4). However, at higher source frequencies, attenuation of the signal may prove to be a limiting factor and the depth of investigation restricted by the electrical skin depth. Currently, these instruments seem to be ideally suited to rapid, large-scale, reconnaissance surveys for the detection of more deep-lying archaeological or geomorphological features, but may yet challenge the quality of traditional earth resistance data for very near surface targets. Rough or uneven ground conditions can be problematic, causing poor coupling between the insulating electrodes and the subsurface.

### *1.7.2 Seismic methods*

Seismic methods use low energy acoustic waves transmitted by vibration through the host medium and can be used effectively in both marine and terrestrial environments. Velocities of seismic waves vary from *c* 200m/s in soil up to 7000m/s in solid geological units and, at the frequencies deployed, can result in relatively long wavelengths, generally >1m. This restricts the archaeological application of seismic methods to relatively large-scale features. For shallow, terrestrial, investigations

**Fig 20** (below) Area magnetic susceptibility survey (a) showing increased response over an area of dense magnetometer anomalies (b). Low responses to the NE correlate with recent soil dumping, but some finer detail is not represented, such as a cemetery (c).

**Fig 21** (above) Bartington MS2 magnetic susceptibility meter in use: (a) in the laboratory with collected 10g soil samples and; (b) on site with a field coil.



the energy source can be as simple as a sledgehammer striking a flat metal plate on the ground, with the resulting vibrations measured by a line of regularly spaced geophone sensors. Each geophone is secured to the ground by a metal spike and consists of a suspended coil wound around a high magnetic permeability core in the field of a strong permanent magnet. Vibrations are then transferred through the spike to the coil to produce a proportional electric current. Multi-core cables are then used to connect the entire array to a suitable multi-channel seismograph that amplifies the signal and records the time when the vibrations reach each geophone.

Energy from a seismic source travels as both a direct wave spreading out through the surface layer and also into successively deeper layers in the subsurface. On meeting an interface between two layers, part of the energy is reflected back to the surface and the remainder continues at a refracted angle. Assuming the lower layer has a higher velocity, an angle of *critical refraction* exists where the incident wave will travel parallel to the interface at this higher velocity, with some of its energy returning to the ground surface as an expanding head wave before the slower direct wave.

This difference in travel path forms the basis of the *seismic refraction* method, where the travel time of the refracted wave is measured from the first received energy for each geophone along the spread from the source, and subsequently used to estimate the depth to the subsurface interface. The seismic refraction method requires the velocity to increase with each subsequently deeper layer, a condition that may not always be met for typical archaeological surveys (Ovenden 1994), but has been successfully applied during the investigation of certain archaeological features, such as the vallum south of Hadrian's wall in Northumberland (Goulty *et al* 1990).

An alternative approach is to use the *seismic reflection* technique that, analogous to GPR, records the amplitude variation of the received signal at each geophone over a suitable time window. For each source location seismic reflection data is often recorded at several locations that share a common mid-point (CMP) between the source and receiver. Multiple observations of buried reflectors are then recorded at successively later travel times and the data reduced to a single trace with a much improved signal-to-noise ratio. Field acquisition with this method is relatively slow compared to other near-surface techniques, but has been successfully applied for a number of archaeological surveys (eg Vafidis *et al* 2003). The potential advantages of multi-fold CMP data acquisition have also been investigated for GPR survey (eg Pipan *et al* 1999) together with the application of powerful seismic processing software, developed for oil exploration, which may equally be applied to GPR surveys over archaeological sites (eg Lehmann and Green 1999).

For shallow terrestrial imaging, seismic methods are disadvantaged by the need to produce high-frequency acoustic sources, to create short wavelengths in the soil, while coupling the source energy effectively to the ground surface. The spacing between the receiver geophones also needs to be reduced to obtain an appropriate sample interval, but this may be restricted where the amplitude of the source can potentially cause damage to the geophone. Attempts have been made to improve the applicability of acoustic techniques (eg Frazier *et al* 2000; Hildebrand *et al* 2002) – particularly using swept-frequency sources – that may well prove fruitful for imaging archaeological features buried under conditions unsuitable for other techniques, such as highly conductive alluvial soils (eg Metwaly *et al* 2005).

### *1.7.3 Borehole methods*

Many geophysical techniques are compromised by either the depth to the target archaeological features or, particularly on urban sites, the presence of considerably disturbed near-surface deposits (eg building rubble). One approach is to introduce the geophysical equipment into the ground through a borehole cored from the surface. This may, for example, take the form of a specially designed GPR transmitter that can be lowered down the borehole and measurements made to a receiver mounted on either the surface or in a second borehole. Equally, seismic sources and geophones, earth resistance electrodes or even magnetometers may be used for borehole investigations. Active source-receiver instruments (eg GPR) allow transmission tomography methods to be applied from deviations of the travel path as the transmitter and receiver are lowered down two separate boreholes.

The major disadvantage with these techniques is the necessity to introduce an invasive borehole into the site that may damage the buried archaeological remains. In some cases the information gained from a borehole geophysical survey may outweigh these concerns, particularly when boreholes have to be sunk for other invasive geotechnical investigations.

### *1.7.4 Micro gravity*

Variations in the local acceleration of the Earth's gravitational field, caused by the contrast in density of the underlying structures, have been successfully used at an appropriate scale to investigate civil engineering or archaeological features (Arzi 1975; Di Filippo *et al* 2000). By far the greatest success has been achieved using appropriate high-sensitivity gravimeters to locate air-filled void features, which, by definition, must demonstrate a considerable density variation from the host structure (eg Blížkovsky 1979; Butler 1984; Fajklewicz 1976; Linford 1998; Linnington 1966).

In essence, a gravimeter consists of a spring-suspended weight and a means to record accurately any varying deflection in the presence of the local gravitational field. Practical instruments must be highly sensitive and compensate both for changes in the ambient temperature and for vibrations at the sampling point. The resulting data must then be further reduced to account for a range of variables, including the diurnal variation of the Earth's gravitational field and even the micro-topography of the site under investigation.

### *1.7.5 Radiometric methods*

Radiation detectors can be used to determine the location and concentration of certain commercially viable radioactive ore bodies, such as uranium. While the attenuation of radioactive particles is relatively high in soil or rock, particularly for *alpha* and *beta* particles that will only travel short distances, *gamma* photons offer more promise (Ruffell and Wilson 1998). The most common sources of gamma radiation are the elements potassium, uranium and thorium that may be found in the constituent minerals forming many archaeological sites. Any contrast or greater concentration of these radioactive elements should, theoretically, be detectable with a scintillation counter of high enough sensitivity. For example, measurements of *gamma*-ray emissions within the walled Roman town at Silchester, Hants, revealed a much lower count rate from the flint and chalk building remains than the substantially higher background value caused by the presence of $^{40}K$ in the soil. Mapping the response with a towed scintillation counter demonstrated significant variations, possibly indicating both the location of building remains and the differing depth of soil cover across the site.

### *1.7.6 SQUID magnetometers*

While relatively common within laboratory-based instruments that measure extremely weak magnetic fields, superconducting quantum interference devices (SQUID) are challenging to deploy in the field because they require very low operating temperatures. Zakosarenko *et al* (2001) demonstrated that SQUID-based systems can also be used for measuring magnetic field gradients and have developed a field instrument specifically for archaeological prospection (Chwala *et al* 2001; Chwala *et al* 2003).

This system is based on a cart-mounted liquid helium cryostat that is able to maintain a Niobium SQUID at a working temperature of 4.2K configured as a special planar intrinsic gradiometer where the two effective sensors are extremely close together (Fig 4d). The magnetic field resolution of the SQUID is approximately 0.00002 nT, about 200 times greater than currently available alkali-vapour magnetometers, and possibly exceeds the sensitivity required to map even the weakest archaeological anomalies encountered in the field. However, this sensitivity is essential for operating as a gradiometer with such closely separated sensors, where the measured gradient will be extremely small, but will also be less affected by local distortions in the earth magnetic field. This, for example, allows the SQUID sensors to be transported in relatively close proximity to a towing vehicle with any residual field removed through post-acquisition processing. While SQUID sensors make sampling much faster than conventional magnetometers (~1000Hz), making them ideal for rapid data acquisition over large areas when operated as a vehicle-towed array, the short gradiometer baseline appears to limit the detection of more deeply buried features.

### 1.7.7 Multi-channel instruments and sensor platforms

The use of vehicle-towed sensor platforms, utilising differential GPS and fluxgate compasses for navigational and positional information, has recently been explored and enables deployment of a combination of multi-channel instruments for the rapid survey of large areas. The University of Leicester has developed a prototype system (Fig 1), configured with an array of caesium magnetometer and electromagnetic sensors. Results from this trial system compare favourably with data collected with a hand-operated caesium magnetometer cart and were completed in a fraction of the time required for the more conventional survey.

Towed multi-channel GPR antennas are also now available, offering the ability to capture very dense data-sets, equivalent to a traverse separation of approximately 0.1m, from a 2m wide instrument swathe. While the initial cost of these systems is beyond most archaeological researchers at present, the benefits of such instrumentation are clear when considering the very large-scale application of GPR survey (eg Neubauer et al 2002).

### 1.7.8 Continuous-wave radar

The majority of commercial ground penetrating radar instruments utilise an impulse source to introduce energy into the ground. More recently, systems using a continuous source have been introduced, where the transmitted frequency is either swept (frequency-modulated continuous wave) or held at a series of steps (synthesised or stepped-frequency) over a range of transmitter frequencies. An inverse Fourier transform is then applied to the recorded frequency domain data to produce a response similar to an impulse GPR.

Somers et al (2005) demonstrate an alternative approach to continuous-wave radio-frequency imaging by introducing a source transmitter beneath the intended target through a small-diameter borehole. The energy from the buried source then passes back up to the ground surface having been modified, in terms of both amplitude and phase, by the illuminated archaeological features. These variations are recorded by a mobile receiver over the site surface and may be processed with appropriate image reconstruction algorithms. The system is analogous to an optical microscope with the RF source acting as a below-stage lamp and the site surface as the lens plane. The reconstruction algorithm can then be adjusted to focus the resulting image on a particular depth of the target beneath the surface.

### 1.7.9 Random-signal radar

If the duration of a transmitted radar wavelet is reduced to an extremely short pulse its energy is distributed over a very wide bandwidth compared to either traditional impulse or continuous wave techniques. A series of ultra-short pulses can be transmitted continuously to form a (pseudo-) random waveform to illuminate buried target objects. The range to the target can then be obtained by correlation of the received signal with the transmitted waveform (Horton 1959). One major advantage of random-signal radars is their very good electromagnetic compatibility, which at low power levels is indistinguishable from background noise. Given the level of regulation applied to the frequency spectrum and electromagnetic compatibility, this technology may eventually replace traditional RF devices. Ground penetrating random-signal radars have been demonstrated and will, no doubt, find suitable archaeological application (eg Xu et al 2001).

### 1.7.10 Thermal sensing

Variations in ground surface temperature can be influenced by the presence of buried archaeological features and are usually recorded by airborne infrared scanners that are able to cover large areas in a single swathe. Some attempts at ground-based thermal mapping have also been made (eg Clark 1996, fig 11), but these have been most successful for investigating historic building fabrics rather than for buried archaeological remains (eg Brooke 1987; Kooiman and de Jongh 1994). Direct measurements of soil temperature with ground-contacting thermocouples have also been investigated, but the heat generated by friction when inserting the probe into the ground was found to slow data acquisition with this method of survey (Bellerby et al 1990).

### 1.7.11 Self-potential

Electrolyte flow in ground water, and across any chemical potential gradient, can cause subtle variations in naturally occurring background potentials, for example across a gradient formed in a concentration of ferric and ferrous ions produced by localised burning of iron oxides in the soil. The application to archaeological prospection was initially investigated by Wynn and Sherwood (1984) and is attractive for its relative simplicity and the low cost of the equipment required.

Field measurements are made between two non-polarising electrodes connected to a suitable high-impedance volt meter. However, care must be taken to account for the influence of topographic changes, buried metal (eg pipelines), stray currents from power sources, ground water movements and changes in temperature, as any of these factors will affect the local self-potential. Even the bioelectrical activity of large plants and trees is sufficient to create a detectable anomaly (Telford et al 1976, 293).

Drahor (2004) provides a summary of the possible sources of self-potential anomalies with regard to archaeological features and demonstrates the success of the technique for detecting burnt structures. However, the advantages of the low equipment costs for this method must be considered against the slow rate of acquisition and the difficulty in obtaining useable field data, and subsequently the often complex interpretation required. Burnt features are also readily detected by the more rapid magnetic techniques that should usually be considered in the first instance.

### 1.7.12 Induced polarisation

The effect of polarisation during the ionic conduction of an electrical current through the soil is a recognised constraint when using direct current for an earth resistance survey (see Part IV, 1.3). Electrode polarisation will also be influenced by subtle membrane polarisation effects associated with buried features and may be measured using a modified earth resistance array. Time-domain measurements are made by applying a square wave signal to the current electrodes, and then recording the decay of any induced polarisation voltage over a period of time shortly after the applied field has been removed. Higher-frequency alternating waveforms, generally between 0.0625Hz and

1000Hz, may also be used for measurements of phase shift in the frequency domain.

Aspinall and Lynam (1968) recognised the possible application of induced polarisation methods for archaeological survey, and subsequent field experiments demonstrated the potential for identifying a buried humus-filled ditch and bank that compared favourably with results from a simultaneous earth resistance survey (Aspinall and Lynam 1970, fig 57). A more recent application of this technique used frequency-domain measurements (also known as *spectral induced polarisation*) to locate a Bronze Age trackway, constructed from wooden planks, found in the Federsee bog near Lake Konstanz, Germany (Schleifer *et al* 2002). The well preserved cell structure of the waterlogged wood exhibited a strong polarisation effect – producing a peak phase shift at a frequency of approximately 5Hz – that located the feature.

While these techniques (sections 1.7.1 to 1.7.12) would not be recommended generally, on specific sites they may find a particular application where other methods fail.

### 1.8 Metal detecting

Metal detectors are EM instruments (*see* Part II, 7.2 and Part IV, 1.5), but mention of them is separated out here because their applications are significantly different to other specialised EM techniques, and because their use solely to find and recover metal objects is contentious. Depending on the instrumentation used, metal detectors emit a pulsed or continuous EM signal that generates detectable and characteristic eddy currents in target conducting metals. Depending on their sophistication, metal detectors can be sensitive to signals from small objects – such as individual coins at depths up to about 0.3m – to larger items at greater depths; also, detectors can be tuned to screen out unwanted responses and to discriminate in favour of certain metals.

Despite initial military incentives, such developments have been driven in part by demand from hobbyists.

Present estimates suggest that there are in excess of 8,000 metal detectorists in England. However, these guidelines refer to the use of metal detectors for archaeological field evaluation, rather than as a hobby. Nonetheless, all metal detector users are strongly advised to abide by the voluntary Code of Practice for Responsible Metal Detecting in England and Wales. This and other valuable information relating to the use of metal detectors can be found through the website of the Portable Antiquities Scheme (PAS) at www.finds.org.uk. English Heritage policy and good practice for portable antiquities and surface-collected material in the context of field archaeology and survey programmes, including the use of metal detectors, is stated in *Our Portable Past* (English Heritage 2006) and can be accessed at http://www.english-heritage.org.uk/upload/pdf/Our-Portable-Past.pdf

Metal detectors are not usually used during the initial evaluation of development sites for their archaeological content. It is possible, however, that desk-based assessment (eg from the HERs and/or PAS database) will reveal that previous finds of metal objects indicate the potential presence of an archaeological site. If this is the case, then metal detector survey might be included in the subsequent field evaluation (integrated with other relevant prospecting methods, as appropriate). In some circumstances it may be that a significant metal detector find is itself the incentive for the evaluation.

As metal detecting usually involves the recovery and removal of artefacts, it is imperative that this form of site evaluation is fully justified, is integrated within an agreed project design, and includes the use of appropriate field methodologies, subsequent conservation, reporting and deposition to an acceptable standard (English Heritage 2006).

Unless used as part of an excavation *(see below)*, metal detecting should normally only take place on land under arable conditions, and as part of a properly structured field survey project.

Metal detectors should only be used to recover material from the contemporary plough-zone, and not from undisturbed contexts; however, metal detecting may also be an acceptable technique on sites or find spots under pasture, where there is unequivocal evidence that the area was subject to arable cultivation in recent years, provided that the recovery of material is restricted to the former modern plough zone. To be effective, a metal detector survey should use skilled operators with suitable instruments, working consistently and systematically over a pre-surveyed grid composed of at largest 10m units (Fig 22). Recovered material should normally be recorded to within these units, or located individually using GPS or electronic measurements.

Metal detecting may in some circumstances be justified over areas that are destined for development and/or excavation, and that have been stripped of topsoil; in these cases controlled metal detecting can be an asset both during the excavation and in the recovery of artefacts from spoil.

Note that metal detecting is not permitted on Scheduled Monuments without a Section 42 Licence (*see* Part II, 7.2), and that restrictions may also apply on other designated sites (http://www.naturalengland.org.uk/conservation/designated-areas/default.htm), and on land under Environmental Stewardship Schemes (http://www.defra.gov.uk/erdp/schemes/es/default.htm). Detecting on land owned by the National Trust must be subject to a Licence Agreement (www.nationaltrust.org.uk/main/md_policy-2.doc).

### 1.9 Geochemical methods

Apart from magnetic susceptibility survey, (*see above*, section 1.6), geochemical methods (phosphate analysis, multi-element analysis and lipid analysis) are not generally used for evaluations. Instead, they are either themselves

**Fig 22** (above) Systematic metal detector survey of an area that has been divided into 10m grids.

the subject of methodological research, or they are used to assist interpretation at an intra-site scale of investigation. A review of geochemical methods is provided by Heron (2001); see also English Heritage (2007).

## 1.10 Remote sensing

Remote sensing is defined as the imaging of phenomena from a distance (Shennan and Donoghue 1992) and is here considered to be distinct from the ground-based remote sensing methods so far discussed.

### *1.10.1 Aerial photography*

Aerial photography (AP) is the most familiar remote sensing technique (Bewley 1993; Bewley and Raczklowski 2002; Palmer and Cox 1993; Wilson 2000) and the aerial photographic record should always be consulted as part of site evaluation. This record is often highly complementary to that obtained by geophysical methods. In many circumstances the AP record will dictate where ground-based methods may be deployed and the latter will often provide exact ground location as well as additional definition and detail. Geophysical methods may be able to respond positively where the AP record is negative, or where surface conditions are unsuitable for photography.

### *1.10.2 Multi-spectral scanning*

Despite the increasing availability of higher-resolution data achieved by airborne multi-spectral scanning (MSS) – from sensors mounted on satellites and on aircraft – this has still not made much impact in the day-to-day evaluation in the UK of sites for their archaeological content. A review of the subject has been provided by Donoghue (2001), and examples of case studies include Fowler (2002), Powlesland *et al* (1997), Shennan and Donoghue (1992), and Winterbottom and Dawson (2005).

### *1.10.3 Remote surface mapping*

Modern remote imaging systems are now able to capture increasingly detailed and accurate topographic information at a variety of scales relevant to archaeological prospection. While digital aerial photogrammetry has seen some application (Stone *et al* 2004), attention is currently focused on the considerable potential offered by lidar (light direction and ranging), and interferometric synthetic aperture radar (IFSAR).

Of these, lidar currently offers the higher level of vertical and horizontal resolution (Crutchley 2006; Holden *et al* 2002), and the resulting digital surface models (DSMs) can be manipulated to enhance the recognition of very slight but significant surface topography (Bewley *et al* 2005). A significant advantage over aerial photography is the potential ability to digitally remove tree cover to create digital terrain models (DTMs) of underlying earthwork features (Devereux *et al* 2005). The value to archaeological evaluation of IFSAR is presently less clear, although elevation data for all of Britain is available at http://www.intermap.com/corporate/greatBrit.cfm.

# 2 Analysis of geophysical data

## 2.1 Data processing

Once geophysical data has been collected it is necessary to process it for interpretation and presentation. The advent of powerful and affordable personal computing equipment has revolutionised this aspect of archaeological geophysics over the last fifteen years and several specialised software packages are now available (Tables 12 and 13). Detailed discussion of the reasons for and application of numerical processing algorithms can be found in a number of textbooks and software manuals (Gaffney and Gater 2003; Scollar *et al* 1990; Walker 2005). Two guiding principles that underlie such discussions bear restatement. Numerical processing can never be a substitute for poor raw data and the surveyor's aim should always be to collect the highest quality measurements in the field. Furthermore, every numerical modification of the original field data should be carried out for a clear purpose and no processing algorithm should be used blind without a full understanding of its implications.

The majority of numerical processing algorithms encountered in archaeological geophysical surveys fall into one of three categories:

(1) those designed to mitigate for artefacts introduced into the data by the prospecting instrumentation and/or strategy;
(2) those that employ generic digital image processing methods to enhance features of interest within the data-set; and
(3) those that use mathematical descriptions of the geophysical measurement process to model or infer information about causative features from the measured anomalies.

### 2.1.1 Mitigating data collection artefacts

*Magnetometer data* Scollar *et al* (1990, 440–5) identify a number of sources of error in magnetometer data resulting from field procedure and environmental factors. Computational procedures have been developed to detect and eliminate the effects of many of these and maximise the clarity of archaeological anomalies

**Table 12** Some of the more commonly used processing software packages available for archaeological geophysics.

| *Manufacturer* | *Software* | *WWW URL* | *Comments* |
|---|---|---|---|
| Geoscan Research | Geoplot 3.00 | http://www.geoscan-research.co.uk/page9.html | wide range of processing options specific to archaeological geophysics |
| DW Consulting | Archeo Surveyor 2 | http://www.dwconsulting.nl/archeosurveyor.htm | very up-to-date interface; good processing and display options |
| David Staveley | Snuffler | http://www.homeusers.prestel.co.uk/aspen/sussex/snuffler.html | free software; aimed primarily at earth resistance survey processing |
| Geosoft Inc. | OASIS Montaj | http://www.geosoft.com/ | offers a wide range of advanced processing options aimed at all forms of geophysics |
| GeoQuest Associates | Insite v3 | No Web site, contact: rockside@manx.net | offers an intuitive and easy-to-use interface |
| Geotomo Software | Res2Dinv 3.55 and Res3Dinv 2.15 | http://www.geoelectrical.com/ | specialist software for inversion of data for electrical sections |

present in the data-set. The most common corrections are discussed below and illustrated in Fig 23 (alternate terms for a procedure are listed in parentheses after each heading):

*Edge matching (equalising sub-grid shifts, micro-levelling):* A large survey will typically be composed of a mosaic of rectangular survey blocks or sub-grids surveyed at different times. One of the first procedures carried out after data collection is to combine these individual sub-grids into a single composite data-set. However, differences in temperature and other environmental conditions as well as recalibration of the magnetometer during the survey can result in sub-grids exhibiting different background measurement levels leading to visible discontinuities between the edges of adjacent sub-grids. Adjusting the mean or median of each sub-grid to a common value (often zero) by addition of a constant to each measurement value within the sub-grid is usually sufficient to eliminate edge discontinuities in magnetometer data (Eder-Hinterleitner *et al* 1996). Only in extreme cases, such as the proximity of large modern ferrous structures, should more sophisticated methods based upon analysis of the local statistics of measurements close to each sub-grid edge be required (eg Haigh 1992).

*Spike removal (despiking):* Magnetometer sensor instability can occasionally cause isolated extreme readings, or spikes, in the survey data, and small pieces of highly magnetised iron lying on the ground surface can cause similar artefacts. Such distracting measurements may be distinguished by their large difference from neighbouring values within the survey sub-grid. Typically a thresholded median or mean filter is used to detect and replace such extreme values (Scollar *et al* 1990, 492). Methods that treat spikes as statistical outliers from the overall data distribution have also been developed and offer the advantage that they can be applied to randomly collected data before interpolation onto a regular grid (eg Ciminale and Loddo 2001).

Where spike removal has been used to suppress anomalies caused by surface iron objects, care should be taken with subsequent interpretation of the data. It is possible for the despiking operation to remove the high-magnitude

**Table 13** Some of the more commonly used processing software packages available for GPR data processing.

| *Manufacturer* | *Software* | *WWW URL* | *Comments* |
|---|---|---|---|
| Geophysical Archaeometry Lab. | GPR-SLICE 5.0 | http://www.gpr-survey.com/gprslice.html | comprehensive processing software supporting all major data formats, GPS integration and data visualisation in 2D/3D |
| GSSI | Radan 6.5 | http://www.geophysical.com/software.htm | advanced processing software supporting GPS integration with additional modules available to extend data interpretation and visualisation in 3D. Supports GSSI data format |
| IDS | GRED-3D, GRED-AGS | http://www.ids-spa.it/ | advanced 2/3D processing software supporting IDS GPR systems; a specialised archaeological software package with pattern recognition algorithms is also available |
| MALÅ | RadExplorer, REFLEXW, Easy 3D, ObjectMapper | http://www.malags.com/software/ | packages to support data processing and visualisation and interpretation in 2D and 3D; supports data input from other manufacturer's native formats together with the RAMAC format |
| Grandjean and Durand (1999) | Radar UNIX | http://www.iamg.org/CGEditor/index.htm | freely available software running under UNIX for non-commercial use for processing GPR profile data. Supports GSSI and SEGY formats |
| Radar Systems Inc. | Prism 2.01, Prism Layers 3D, Prism Easy 3D | http://www.radsys.lv/ | software for the acquisition and post-processing of data collected with the Zond GPR system, also compatible with SEG-Y and GSSI data formats |
| Sandmeier | Reflexw | http://www.sandmeier-geo.de/ | extensive GPR and seismic data processing and visualisation tools; supports GSSI, Mala, PulseEkko, SEG-Y and other seismic data formats |
| Sensors & Software | EKKO_View, EKKO_Mapper 3, EKKO_3D | http://www.sensoft.ca/products/pulseekko/p_software.html | packages to support the processing and display of profile, time/depth slices and 3D visualisation of GPR data captured in the PulseEkko data format |
| Tzanis (2006) | MATGPR | http://users.uoa.gr/~atzanis/matgpr/matgpr.html | a suite of free GPR processing routines and a GUI interface for the Matlab numerical computing environment; compatible with GSSI, Mala, PulseEkko, SEG-Y and Seismic Unix data formats |

positive peak of such small dipolar anomalies but leave the adjacent values associated with the negative pole, which are often of smaller absolute magnitude. Without the positive peak to provide context, these latter can be mistaken for negative archaeological anomalies.

*Destriping (unbunching):* Magnetometer surveys collected in zigzag mode can exhibit striping where successive traverses appear as alternating light and dark bands when the data is plotted. This is because magnetometers can exhibit directional sensitivity (sometimes called 'heading error'): a change in the value measured by the magnetometer depending on the direction it faces relative to magnetic north. In fluxgate gradiometers it is usually caused by slight differences in alignment between the two differential sensors, and optically pumped magnetometers may also exhibit an inherent directional sensitivity.

The standard method of correction is to assume that the bias caused by this effect is constant over an entire traverse and to subtract a constant value from all readings on the traverse, such that their mean is set to zero or to a value common to all traverses (eg Ciminale and Loddo 2001). Such techniques also simultaneously remove the long-term zero drift exhibited by most types of magnetometer, providing the time taken to complete each traverse is short relative to the rate of instrument drift. However, where traverses are long (~100m), more sophisticated linear regression techniques may be required instead (Tabbagh 2003).

When destriping, care should be taken that linear anomalies parallel to the traverse direction are not erroneously removed by the process, particularly when their length is close to or greater than the traverse length and their magnitude is similar to the biases caused by the directional sensitivity. Eder-Hinterleitner *et al* (1996) describe a destriping method that can protect such parallel anomalies against erroneous removal but only if they are wider than the survey traverse separation. Hence, every effort should be made to reduce instrument directional sensitivity in the field rather than relying on post-acquisition processing to remove severe striping.

*Correcting line displacement errors (destaggering):* Magnetometers are often set to take readings at regular time intervals and the position along the traverse at which each reading was taken is calculated on the assumption that travel speed was constant. However, variations in traversal rate can occur (because the operator encounters a steep incline and has to slow down, for example) and this can result in the sensor not being at the correct position when a reading is taken. When traverses are walked in zigzag fashion, deleterious effects can be pronounced with linear anomalies crossing the traverses having their peak positions displaced in opposite directions on alternate traverses, leading to a 'staggered' appearance in plots of the data. Often, shifting each traverse to maximise cross-correlation with the two neighbouring traverses will correct for the effect (eg Ciminale and Loddo 2001); however, where significant variations in pace occur during a single traverse, re-interpolation of the sample interval may also be necessary (Eder-Hinterleitner *et al* 1996). Such methods can only estimate the displacement that has occurred by making assumptions about how anomalies appearing on adjacent traverses should match up. Particular care should be taken to ensure that linear anomalies running diagonally to the traverse direction are not altered so that they appear perpendicular to the traverses after this operation. Thus, diligent field procedure should always be employed to minimise the need for post-acquisition correction of line displacement errors.

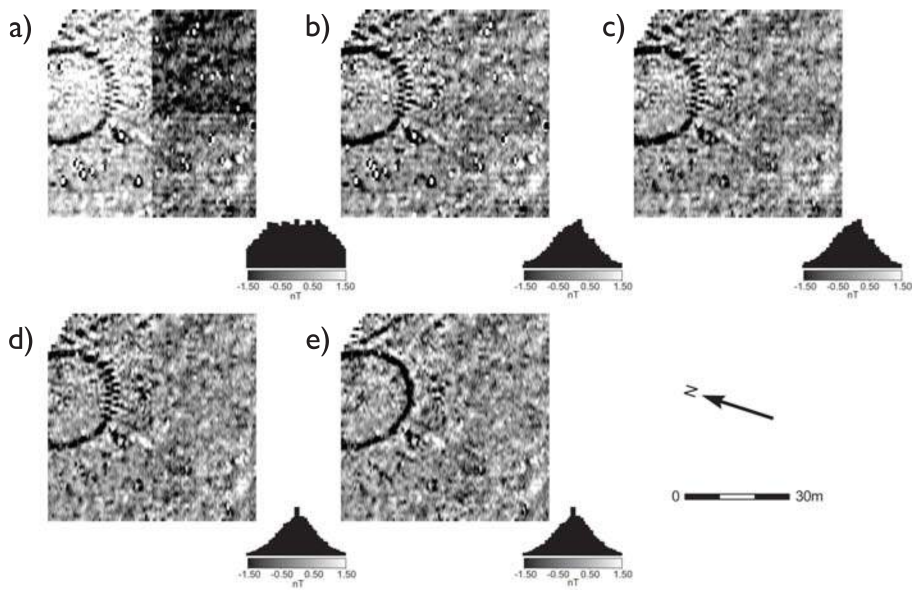



**Fig 23** (above) (a) Composite plot of four sub-grids combined with no corrections; (b) the same four sub-grids combined, following edge matching, whereby discontinuities between sub-grids are reduced; (c) then with additional spike removal where distracting dipolar responses are lessened; (d) then after destriping, which had been most evident on the right half of the area; (e) after correcting line displacement errors with the most obvious effect on the circulinear anomaly, although other anomalies have also been clarified. This manipulation of the data is evidenced by the positional adjustment of the incomplete lines in the top left corner.

*Earth resistance data:* Scollar *et al* (1990, 345ff) outline the problems that can occur with earth resistance measurements. The majority are best avoided by careful attention during data collection. However, two types of error are often impossible to eliminate completely and are susceptible to mitigation by numerical procedures.

*Edge matching (equalising sub-grid shifts, micro-levelling):* Weather conditions may change during the course of a large earth resistance survey, causing changes in the soil moisture content. Such changes will influence the average resistivity of the sub-surface and it is possible that adjacent survey sub-grids measured on different days will exhibit a discontinuity along their common edge. Where changes in soil moisture conditions have been relatively minor, corrective procedures similar to those used for magnetometer surveys usually suffice. However, more severe variations in conditions may require more complex pre-treatment to individual sub-grids such as re-scaling the data range or the removal of a first order trend. In extreme cases it may not be possible to entirely remove edge discontinuities caused by changes in field conditions.

*Spike removal (despiking):* Surface conditions such as concentrations of stones or uneven topography may result in poor electrical contact between the ground and one or more of the earth resistance electrodes. This can result in anomalously high or low resistance values being measured. As such measurements will exhibit large differences from neighbouring values it is possible to detect and remove them using the same types of procedures used to remove spikes in magnetometer surveys. However, wherever possible, such instances of high contact resistance should be detected and re-measured in the field as the survey progresses because post-acquisition removal of large numbers of such spikes reduces the number of truly independent measurements in the resulting data-set.

*Ground penetrating radar data:* The level of post-acquisition processing required for GPR data will depend, in part, on the specific aims of the survey (eg for the production of individual profiles or multiple traverse data-sets, or for display as amplitude time or depth slices) and, perhaps to a lesser extent, the type of radar equipment in use. Useful summaries of appropriate GPR data processing techniques can be found in Annan (2004) and Daniels (2004), and more specific archaeological applications are considered in Conyers and Goodman (1997), Conyers (2004) and Leckebusch (2003).

As with other geophysical methods good field technique will minimise many data acquisition artefacts and particular care should be taken to maintain good antenna coupling with ground surface. The GPR data processing procedures discussed below represent general considerations arising under typical field conditions and should be read in conjunction with sections 1.4 *(above)* and 2.1.3 *(below)*.

*Individual trace repositioning and interpolation (rubber-banding):* The majority of GPR data will be collected at a high density along-line sample interval using either a system triggered by a distance measuring odometer wheel or continuous time-based trace acquisition with additional positional information. This positional information may be provided through the manual insertion of fiducial markers as the antenna passes distance markers along the survey guide rope or, for more recent instruments, simultaneous GPS measurements. Regardless of the system in use it is often necessary to reposition and interpolate the raw GPR traces to account for slight variations in the collected sample density because of changes in the speed of acquisition, odometer wheel slippage or calibration error, or the lower density of GPS or fiducial data compared to the rate of GPR capture. Despite the inherent error associated with all (semi-) automated methods of positional control, adequately processed data-sets contain few, if any, positional artefacts and offer considerable advantages in speed of data acquisition compared to manually triggering each trace.

*Zero offset removal (DC shift or dewow):* This process corrects the mean value of each trace to a near zero value to account for any DC offset that may have been introduced by the sampling electronics during the period of data acquisition.

*Time zero alignment:* Some temporal down-trace variation of the first recorded signal on each trace may occur from electronic drift across a data-set. This drift can be corrected by aligning the common direct-wave response present in every trace, often through picking and adjusting to a single minimum amplitude threshold (eg Conyers 2004, 90–1).

*Time varying signal gain:* An appropriate gain should be applied to amplify lower amplitude, later reflections caused both by the attenuation of the signal in the propagation medium and by the spreading loss of the expanding radar wave front with depth (eg Jol and Bristow 2003, 20).

An appropriate down-trace time window should be chosen, which may include the air-wave response to improve resolution of very near-surface non-planar reflections; but care should be taken to avoid the suppression of significant horizontal reflectors, if present (eg Conyers 2004, fig 6.3).

*Frequency filtering:* Both low-frequency energy, associated with antenna–ground interactions, and high-frequency noise can be suppressed by the application of suitable frequency filters, generally matched to the centre frequency of the specific antenna in use.

### *2.1.2 Image enhancement*

In some situations image enhancement methods can be employed to accentuate anomalies of interest within the survey data while suppressing the effects of those considered less archaeologically relevant. A wide variety of such algorithms exists, many of which are not specific to geophysical data-sets but are generic to all types of digital image. Scollar *et al* (1990, 488ff ) review a number of those most relevant to archaeological geophysics. Perhaps the most commonly applied are convolution operators that calculate a weighted local average around each data value then either deduct it from or substitute it for the original value (often termed high- and low-pass filtering, respectively). Low-pass filtering can be used to suppress the effects of uncorrelated measurement noise between adjacent readings while high-pass filtering can remove the effects of large-scale geological trends within the data allowing archaeological anomalies to be discerned more clearly (Fig 24).

Image enhancement is usually unnecessary for magnetic gradiometer data, but it should be considered for earth resistance data where archaeological anomalies are often superimposed upon larger-scale trends caused by geological and hydrological changes. Where such techniques have been applied it is essential that they are identified and explained. Reference to standard texts on the subject is acceptable, although the choice of any variable parameters should be detailed. All such algorithms accentuate some aspects of the data at the expense of suppressing others, and many have the potential to produce spurious processing artefacts, which may then be misinterpreted by either the contractor or the client. To guard against this eventuality the survey report should explain why a particular series of processes was necessary, summarising the benefits to interpretation. It is misleading to conceal the poor quality of the original data by applying merely cosmetic enhancements.

### *2.1.3 Modelling and inversion*

Data modelling considers idealised forms of the types of buried archaeological feature that might be detected in a geophysical survey and, by describing mathematically the physical processes by which such features influence surface geophysical measurements, predicts the form of geophysical anomaly that should result. By comparing a set of synthetic anomalies with those detected in real survey data it is possible to estimate parameters such as the shape and burial depth of archaeological features. Data inversion attempts to predict causative archaeological features directly from survey data by applying the mathematical inverse of the operators used for synthetic modelling to the field measurements.

Such techniques are usually not necessary for standard archaeological area surveys where the layout of archaeological features can be determined from a plan view of the geophysical anomalies. However, the anomalies generated by vertical electrical sections are often complex and the shapes and burial depths of causative features cannot always be directly inferred from the geophysical measurements. For this type of data, numerical inversion techniques may be applied to clarify the vertical definition of any buried archaeology.

The process often proceeds iteratively, first inverting the data, then modelling the measurements that would be expected, given the inferred features, and then using a comparison between the modelled and real data to improve the inversion. This process is repeated until the modelled measurements match the real measurements to an acceptable degree (eg Fig 25; Loke and Barker 1996). While not generally required for standard archaeological surveys where the objective is to identify the presence of archaeological features, modelling techniques can also be applied to magnetic data to estimate characteristics of the causative archaeological features. As magnetic anomalies are not unique to one particular causative feature (Blakely 1996, 216), it is usually not possible to apply inversion methods such as those used for electrical sections. However, by making a number of reasonable simplifying assumptions it is possible to model the geometry of the buried features likely to have caused a particular detected anomaly (eg Eppelbaum *et al* 2001; Neubauer and Eder-Hinterleitner 1998).

Forward modelling of GPR data is both complicated and computationally intensive compared to the inversion of earth resistance or magnetic data (eg Conyers and Goodman 1997, plate 2a; Daniels 2004, 37–67, C3). However, attempts are often made to reduce the complex transmitted signal, or wavelet, produced by a GPR to an ideal impulse response function through wavelet optimisation or deconvolution techniques. This process is often further complicated by the time variant attenuation of the incident wavelet as it passes through the subsurface, but deconvolution can often prove effective for the suppression of certain repetitive down-trace signal artefacts such as antenna 'ringing' over near-surface conductive objects (eg Conyers 2004, 126–8). In addition, the use of wave-front migration techniques to collapse the hyperbolic response from point-reflectors – caused by the progressively spreading pattern of radar energy through the ground – may also be considered as a form of data modelling (eg Conyers 2004, 128–9; Linford 2006, 2237–8). However, migrated GPR data-sets are rarely, if ever, confirmed by the application of a suitable forward model and subsequent comparison against the original data. Migration can often aid the resolution of detailed structure within complex anomalies caused by the overlapping response of many individual point-source targets, but may not be beneficial to every data-set.

## 2.2 Data display

Graphical presentation of geophysical survey data is an essential step in visualising, understanding and interpreting the results. Appropriate data plots should be provided in the survey report to support the interpretations made by the practitioner and to help both specialist and non-specialist readers to follow the reasoning set out in the report text. A number of different display formats have been developed for

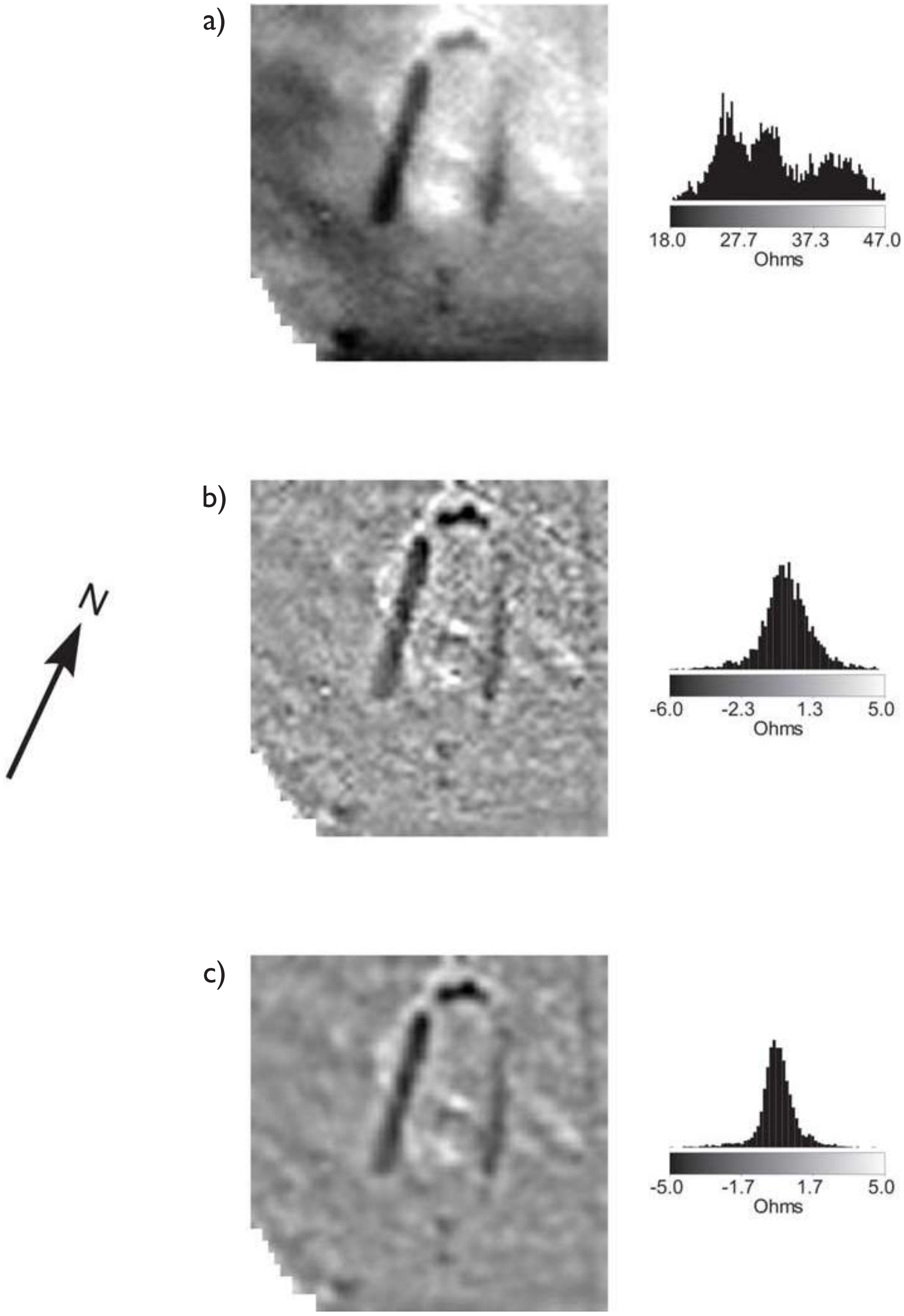



Fig 24 (left top) Earth resistance data over a U-shaped long barrow ditch defined by low resistance over a variable background response, showing the effect of high pass and low pass filtering: (a) raw data showing variable background resistance across the surveyed area; (b) removal of variable background using a 3m radius Gaussian high-pass filter; (c) main archaeological responses in the data further emphasised by smoothing with a 1m radius Gaussian low-pass filter.

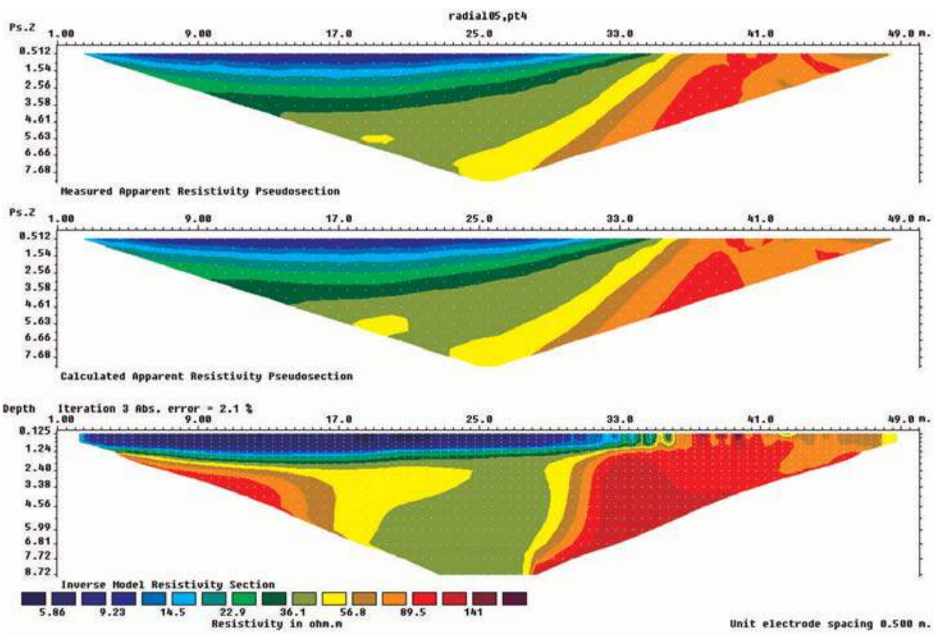



Fig 25 (left bottom) Inversion of an electrical section over a ditch section, which shows as a low resistance (dark blue) anomaly. The top picture shows the pseudo-section created from the raw electrical measurements, while the bottom picture shows the best-fitting subsurface model calculated by inversion of these measurements. The middle picture shows the estimated pseudo-section that should have been measured for the modelled subsurface.

geophysical data and the benefits and limitations of each are summarised below. For most survey reports, greyscale plots are the primary presentation format, supported by some of the plot types discussed below where these aid exposition and interpretation.

### *2.2.1 Trace plots (X–Y traces, stacked traces)*

Before the development of portable digital computers, trace plots were a common method for displaying magnetometer surveys, as the analogue output from the magnetometer could be directly connected to an X–Y chart recorder, which displayed the data as it was collected (Clark and Haddon-Reece 1972–3). Each instrument traverse is depicted as an approximately horizontal line but the line trace deviates above or below a base (zero) level in proportion to the magnitude of the magnetometer measurement at that position (Fig 26a). Subsequent traverses are plotted parallel to the first, offset at increasing distances up or down the page.

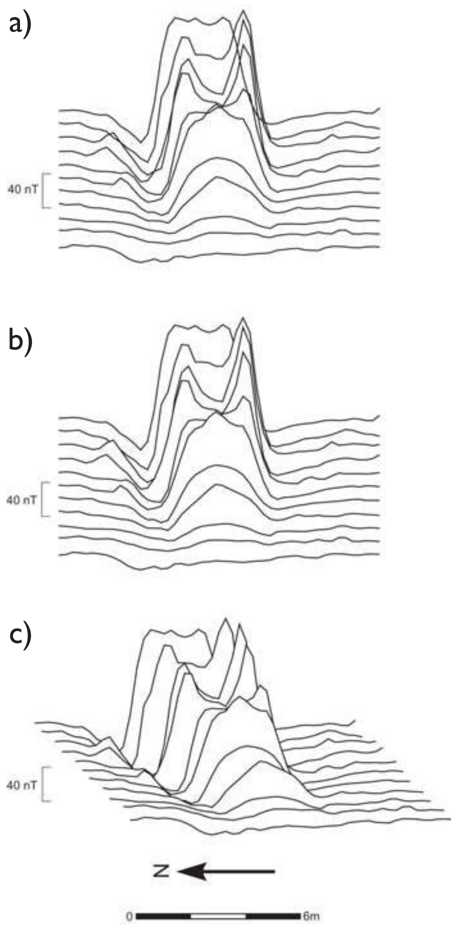
In its simplest implementation the trace plot has only one variable plotting parameter – the vertical scale – which specifies how far the trace should deviate above or below the base level in response to a unit change in measurement. Thus the trace plot has a relatively low degree of operator subjectivity and anomalies of widely varying magnitudes can all be discerned on the same plot. Additionally, unlike other common techniques that display the data in plan, the trace plot depicts vertical profiles across anomalies, which makes the distinctive signatures of some types of anomalies readily apparent (such as the distinctive kiln anomaly in Fig 26). Hence, they provide a useful initial impression of the relative overall variation in magnitude of anomalies in an unprocessed data-set and, particularly when used to plot small areas extracted from the overall survey, can greatly aid interpretation of specific anomalies. However, for the trace plot to be useful, it is essential that a graphical indication be provided showing the vertical scale used to represent variations in the measured values.

A drawback of the profile view is that an excessive number of extreme measurements (especially spikes) in the data-set can render the plot visually unintelligible. In this case it is necessary to truncate (or clip) such values before display. The very large magnetometer surveys that are now practical with modern multi-sensor instruments can also cause problems as the sheer number of traverses needing to be displayed means that there is not enough space in the plotting area to distinguish one from the next. Thus, it is now not always practical for a survey report to provide a trace plot of the unprocessed survey data in its entirety, although plots of sub-areas containing distinctive anomalies can still be advantageously employed to support interpretations.

Elaborations to the basic trace plot have been introduced to create a more solid three-dimensional appearance. Traverses plotted near the bottom of the plot are considered to be closer to the viewer than those farther up, and a straightforward method to give a visual impression of depth is to hide line segments in the background that would be obscured by anomalies rising up in the foreground (hidden line removal) (Fig 26b). The impression can be strengthened by laterally offsetting traverses in proportion to their distance from the viewer to provide a pseudo-isometric view (Fig 26c).

### *2.2.2 Contour plots*

Contour plots display the survey data in plan using a series of contour lines (or isopleths) to show the positions where the magnitudes of the geophysical quantity being measured cross one of a predetermined set of threshold values (Fig 27) (Davis and Sampson 1986, chapter 5). If the survey data contains mainly localised variations from a base level that is relatively constant over the whole area, it is possible to produce an effective contour plot



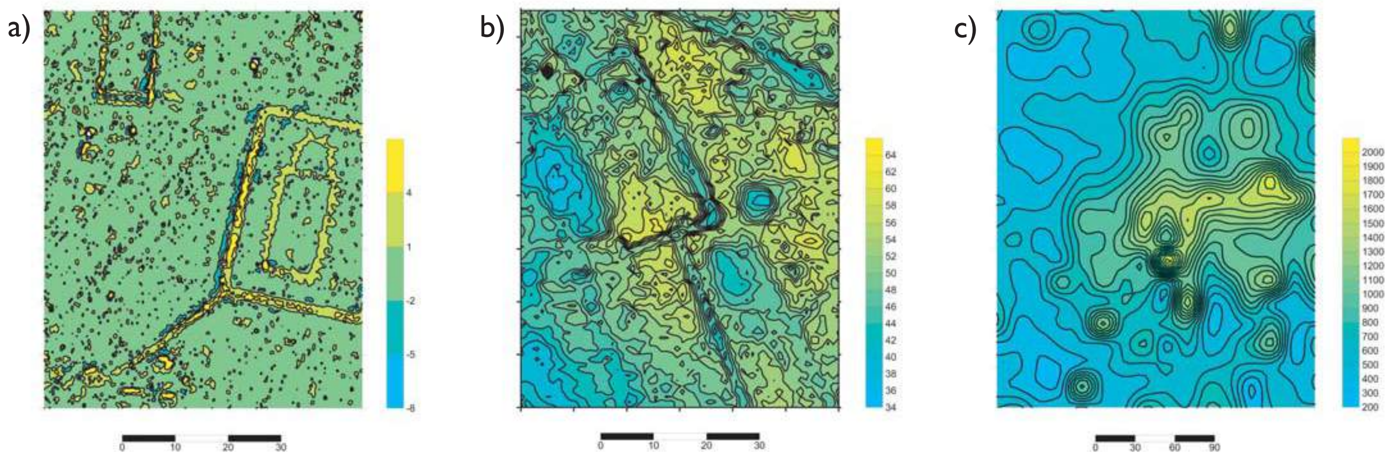




**Fig 26** (above top) (a) Basic trace plot of a magnetometer survey over a kiln feature; (b) the same trace plot with hidden lines removed to give an impression of solidity; and (c) replotted with successive traverses increasingly offset to give a pseudo three dimensional effect.

**Fig 27** (above bottom) Colour contour plots: (a) magnetometer data where the 1nT and 4nT contours outline the linear footings of timber buildings and adjacent enclosure ditches; (b) earth resistance data set on a varying regional background where the choice of contouring has been less successful at isolating the anomalies; and (c) smoothly varying magnetic susceptibility data-set with elevated readings coinciding with the location of a Roman villa and lower values associated with an adjacent river floodplain.

that outlines the important archaeological anomalies (Fig 27a). However, the choice of the particular data thresholds to contour is critical, so contour plotting involves a high degree of subjectivity. Where the background data level varies across the plotting area, many different contour values are needed to emphasise localised details against all the different base levels. Furthermore, whatever algorithm is used to create continuous contours from the data, the process intrinsically involves a degree of low-pass filtering, which will tend to smooth out the smaller-scale anomalies that are typically of most interest in archaeological surveys.

The net result of trying to select enough contours to counteract these problems can be a very 'busy', visually unintelligible, plot (see for example Fig 27b; and Scollar *et al* 1990, fig 8.35). Hence, contour plots tend not to be suitable for depicting detailed area surveys containing complex archaeological anomalies. However, for low-resolution data-sets where the measured geophysical property varies smoothly across the survey area (Fig 27c), or to emphasis the large scale regional trends in a more densely sampled survey, contour plots can still be an effective means of presentation. They can also be deployed advantageously to highlight very high magnitude thermoremanent anomalies in magnetometer surveys. Wherever contour plots are used, it is essential that the contour values are labelled, as otherwise it is impossible to determine which are the peaks (highest values) and which the troughs (lowest values) in the plot.

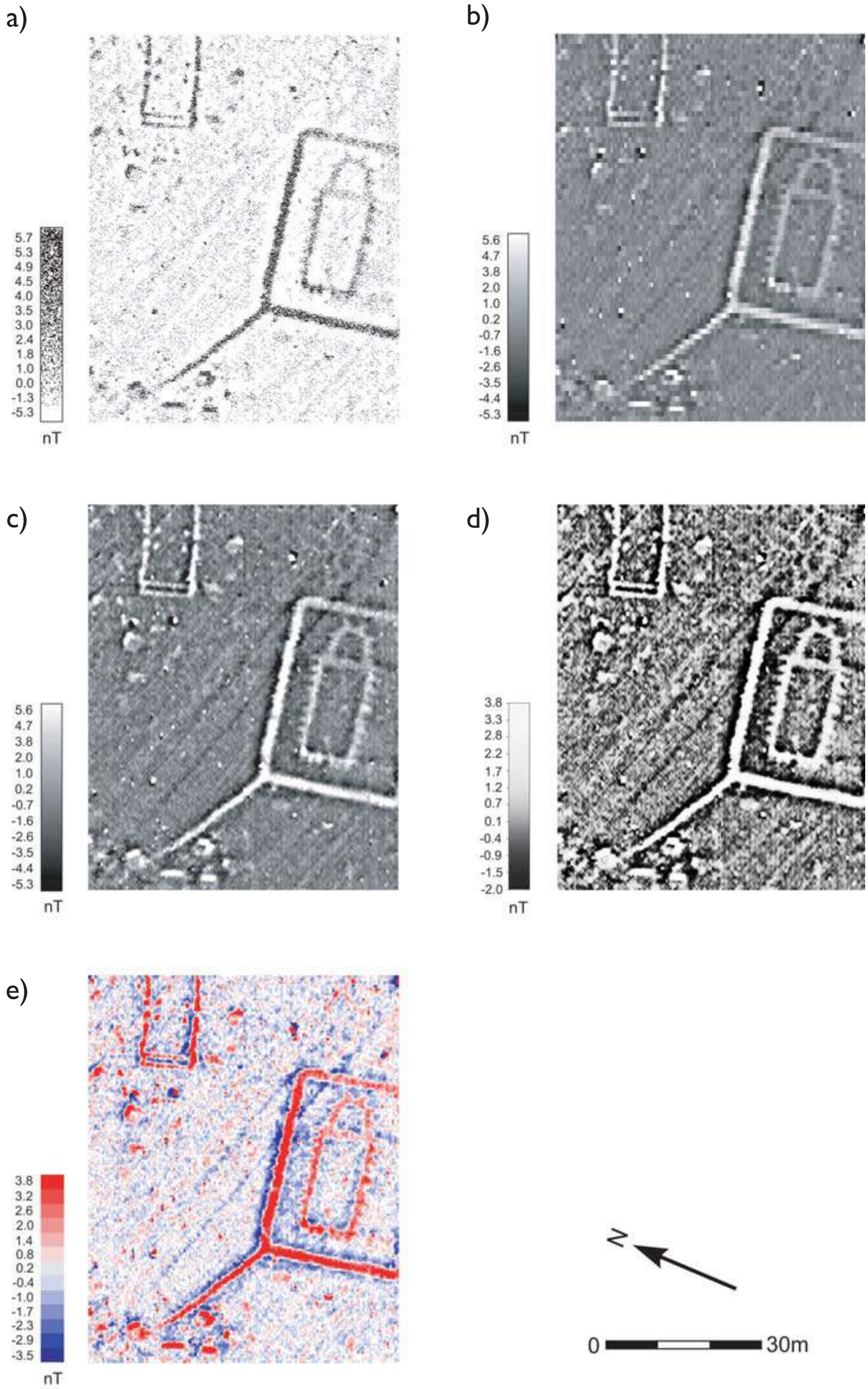



**Fig 28** (above) Different display options for magnetometer data: (a) dot density plot; (b) linear greyscale or half-tone plot (no interpolation); (c) linear greyscale plot of interpolated data; (d) equal area greyscale plot and; (e) plot produced using a colour palette.

### *2.2.3 Dot density plots*

Dot density plots (Fig 28a) also plot the survey area in plan and were a popular means of displaying data-sets prior to the advent of affordable high-resolution computer graphics when computer monitors were monochrome and printers did not have high resolution half-tone or colour printing capabilities. The plotting area is divided into small sub-rectangles each corresponding to the footprint of one geophysical measurement. Black dots are placed randomly within each sub-rectangle with the total number assigned being determined according to the magnitude of the geophysical measurement at that point. The effect approximates to that of a printed greyscale plot, albeit one in which the half tone is readily visible. Dot density plots share many of the advantages of greyscale plots outlined below. However, the random assignment of dots means that the same plot, using the same plotting parameters, can appear different each time it is generated, possibly affecting which anomalies are highlighted or suppressed. Also, the need to sub-divide the plotting area into relatively large sub-rectangles, coupled with the fact that randomly placed dots do not create the same visual effect as a continuous periodic half-tone pattern, can emphasise discontinuities between adjacent measurements and lead to a blocky appearance.

### *2.2.4 Greyscale plots (greytone plots)*

Greyscale plots (Fig 28b–d) are now the most commonly used and versatile method of displaying geophysical data in plan. As with dot density plots the survey area is divided into sub-rectangles each corresponding to the footprint of one field measurement, but in this case the rectangles are filled with a shade of grey related to the magnitude of the geophysical reading at that point. With modern computer graphics capabilities a large palette of grey shades can be used (typically between 100 and 256), providing a continuous variation in tone between white and black. This continuous gradation suppresses the perception of discontinuities between adjacent measurements, allowing the eye to concentrate on trends across the survey area; and the effect can be strengthened by interpolating the data to a higher resolution, so that each shaded sub-rectangle corresponds to one pixel on the display device being used.

The greyscale can be assigned with white representing the lowest measured values, progressively darker shades of grey corresponding to higher values and black representing the highest values of all; or the assignment can be reversed, with black used for the lowest values and white for the highest (practitioners familiar with dot density plots often favour the former while those from an image processing background tend to use the latter). Furthermore, the thresholds between the measured values shaded with different levels of grey can be assigned in different ways, the most common choice being a linear mapping from the survey data's range of values, although log-linear and equal-area (or histogram-equalised) assignments are also useful, depending on the statistical characteristics of the data being plotted. From the foregoing it should be clear that it is essential for every greyscale plot be accompanied by an assignment key to show how the measured values map to the shades of grey in the plot.

Greyscale plots of archaeological geophysical data often look similar to vertical black and white air photographs, a form of presentation readily familiar even to those with no experience of geophysical data interpretation. A variant of the basic plot, the shadow plot, strengthens this effect by pre-processing the survey data to accentuate edges and sharp gradients running in a pre-selected direction. The effect is similar to an air photograph of earthworks taken in strong oblique sunlight and can be effective in emphasising linear anomalies sharing a common alignment. A second variation is to replace the greyscale with a palette of different colours to produce a false-colour plot (Fig 28e), similar to the way that differing land surface elevations are colour coded in an atlas. However, it should be noted that the eye will tend to be drawn to the interfaces between contrasting colours, so that the overall visual effect will be that of a coloured contour plot. As with contour plots, careful choice of the colour thresholds can produce results that dramatically emphasise particular anomalies while other details are suppressed in the process. It is thus strongly recommended that where colour plots are used, a greyscale plot of the same data is also shown.

### *2.2.5 Three-dimensional views*

The isometric trace plots mentioned above can incorporate diminution towards a horizon point to provide perspective and enhance their three-dimensional impression. Introduction of a second set of parallel lines orthogonal to the instrument traverses then creates a wire-frame surface plot (Fig 29a) and the quadrilaterals so formed can be coloured and shaded (Fig 29b) to render the data as a solid three-dimensional surface (see for example Foley *et al* 1991, chapter 15). An extension to this type of surface plot is the 'drape', where the shape of the plotted surface is determined by the actual topography of the area surveyed, whereas its colouration is determined by the geophysical measurements – effectively a greyscale or false-colour plot is draped over the surface topography of the site (Fig 29c). Where the plotted surface represents site topography, exaggeration of the scale of the vertical axis is often an effective way to highlight subtle changes in elevation. In this case it is important that the plot key makes clear the factor by which the vertical axis has been scaled relative to the two horizontal axes, in addition to the usual requirement for a grey/colour scale assignment key.

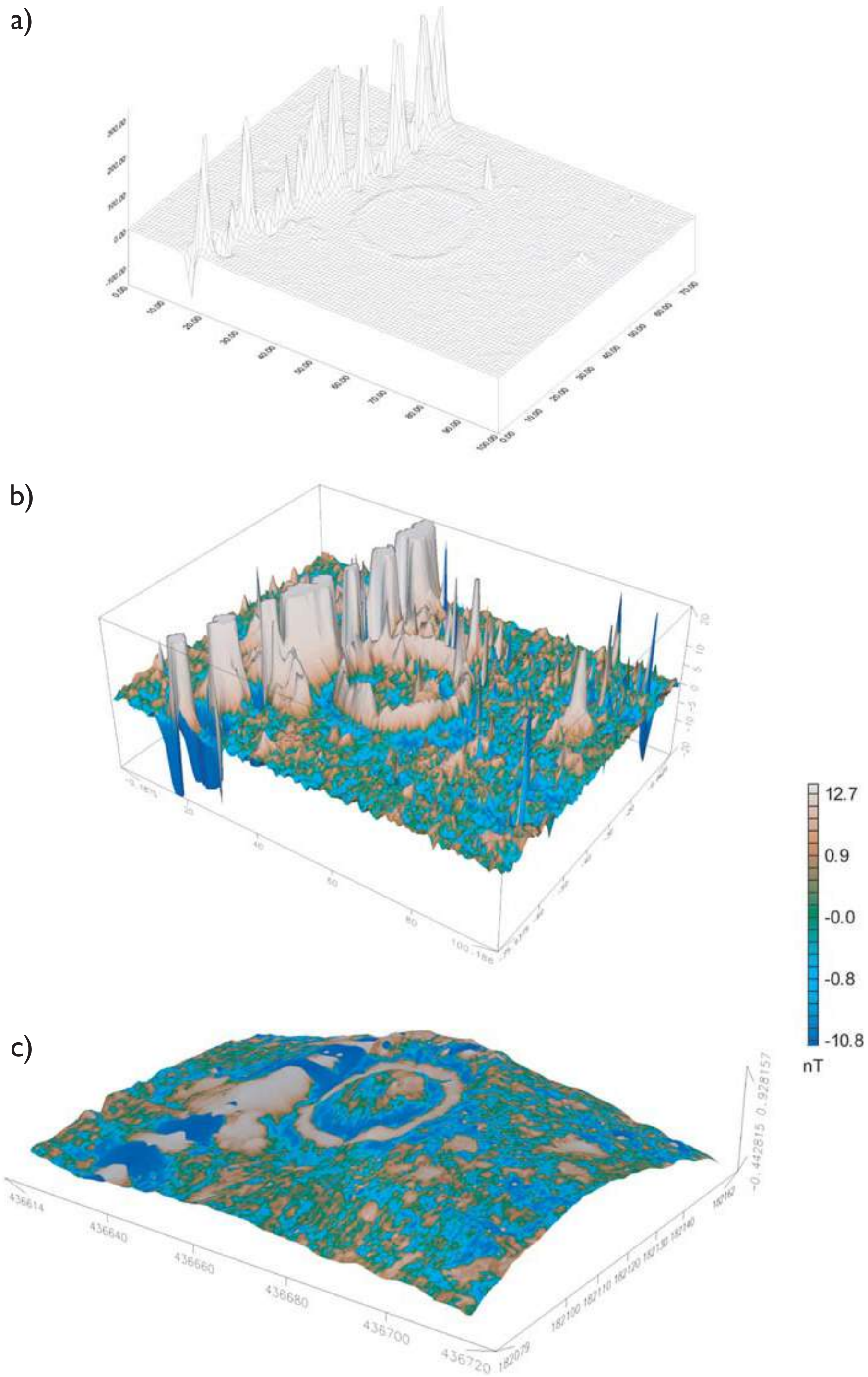



**Fig 29** (above) Three-dimensional representations of geophysical data: (a) a wire frame plot (with vertical scale exaggerated); (b) a shaded surface plot (with vertical values truncated to ±20nT); and (c) a plot of the data draped over a digital terrain model (with vertical scale exaggerated).

A different type of three-dimensional view can be used where a 3D volume of data has been imaged (as is often measured with GPR or ERT equipment). The resulting data can be displayed as either a false-perspective cut-away model or as an iso-surface where a threshold value is chosen and all parts of the volume where the geophysical value is below this threshold are considered transparent, while those parts above the threshold are rendered opaque (*see* Fig 16d). Iso-surface plots can assist in elucidating spatial relationships between anomalies associated with individual causative features, although the selection of an appropriate threshold level requires careful judgement.

All types of three-dimensional rendering can provide visually striking representations of the survey data but it should be borne in mind that they will emphasise anomalies in the foreground of the view while obscuring those farther back. Thus the choice of viewpoint when creating the plot will determine which details are visible, and it should be recognised that plots from more than one different viewpoint may be necessary to adequately display all parts of the survey area.

Where a computer display screen is being used rather than a hard copy device, it is possible to interactively change the viewpoint or animate a sequence of views as a 'fly-through' to overcome this difficulty, although it is not possible to reproduce this type of interactive presentation in the printed report – which will be the authoritative reference for the survey project. Hence, while three-dimensional views can be used to good effect to highlight specific details within a geophysical data-set, they should not be the only type of graphical plot presented, but should be supported by more traditional plan representations, such as greyscale plots.

## 2.3 Data interpretation

Raw geophysical data can be obtained, processed and presented, one way or another, by following instruction manuals and course notes. However, the interpretation that follows generally requires a wider experience – encompassing an understanding of the site conditions and their history, the principles of archaeological geophysics, as well as the foibles of instruments and survey methodologies. A good knowledge of archaeology is of course important, as well as of geology and geomorphology. Ideally an interpreter will already have such experience, and will preferably have conducted and/or directed the fieldwork concerned personally (although it need not follow that the fieldworker is thereby automatically qualified in the subsequent interpretation of the data).

The factors that require consideration in arriving at an interpretation will vary from site to site, but should normally include at least the following:

| *natural* | *artificial* |
|---|---|
| solid geology | landscape history |
| drift geology | known/inferred archaeology |
| soil type | agricultural practices |
| soil magnetic susceptibility | modern interference |
| geomorphology | survey methodology |
| surface conditions | data treatment |
| topography | any other available data |
| seasonality | |

Any interpretation must normally take into account each of these factors, the emphasis varying according to circumstance, and should include consultation with colleagues and other relevant specialists where necessary. For instance, experience shows that where there is even the most meagre earthwork survival, the combination of field survey and geophysical survey is highly beneficial to their joint interpretation. The degree of usefulness of the former will increase according to the condition of the earthworks and the intensity of the field survey. Likewise, where earthworks have been completely ploughed out, comparison with aerial photographic analysis and evidence from historic maps will also yield useful interpretative data.

Arriving at an interpretation that takes into account so many factors can be a finely balanced process and the outcome will be coloured by, and depend significantly upon, the experience of the interpreter. Above all it is crucial that any interpretation draws a clear line for the reader between demonstrable fact that is securely supported by the data, and less secure inference. Here, we would only warn against a tendency to see and attribute significance to every detail – in other words, to over-interpret. Minutely annotated plots with laborious textual referencing of every apparently significant anomaly stretch the credibility and wear down the patience of readers. Generally speaking, it is preferable to exercise as much objectivity and restraint as possible, and to err towards under-interpretation, resisting the embellishment of plots with wishful patterns and details.

While much importance is given to the graphical presentation of results (*see* Part II, 4.9), and it is often this, not the text, that holds the client's attention, it is important that the graphics are supported and complemented by precise written discussion as well. Occasionally, contractors have risked applying percentage 'confidence ratings' to the interpretation of geophysical anomalies – an acceptable additional option only on the clear understanding that such ratings are partly subjective and potentially fallible assessments, applicable only to the specific survey data concerned.

Refinement of the interpretation of geophysical surveys is, to a significant degree, dependent upon the feedback of 'ground-truth' following the survey fieldwork. Wherever possible every effort should be made to encourage such feedback and its subsequent dissemination into the general pool of accumulated experience (*see* Part II, 5). To aid this process, curators can stipulate that trial trenching and excavation reports are copied to the geophysical contractor, that mitigation and publication briefs make allowance for the results of geophysical surveys, and that reporting includes the post-excavation comments of the geophysical contractor (if appropriate).

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## Glossary

**area survey** the gathering of geophysical data over an area, usually across a pre-defined survey grid, resulting in a two-dimensional plan image of the results – the term thus excludes isolated survey transects; 'detailed area survey' refers to surveys where data is gathered at intervals of 1m x 1m, or less

**alkali-vapour magnetometer** a type of magnetometer capable of making very sensitive measurements of a magnetic field by observing changes in the quantum energy states of electrons exposed to it. The method employed is most readily applied to alkali metals in the gaseous state, as these chemical elements have a single unpaired electron in their outer shell. Also known as optically pumped magnetometers (*see* Part IV, 1.2).

**appraisal** a rapid reconnaissance of site and records to identify (within the planning framework) whether a development proposal has a potential archaeological dimension requiring further clarification (IFA 2001)

**brief** an outline framework of the archaeological circumstances that have to be addressed, together with an indication of the scope of works that will be required

**brownfield** any land that has been previously developed

**caesium magnetometer** currently the most common type of **alkali-vapour magnetometer**

**centre frequency** a nominal value for a GPR antenna describing the dominant operating frequency that will influence the depth of penetration and resolution (*see* Part IV, 1.4)

**conductivity (σ)** the ability of a material to carry an electric current measured in units of millisiemens; also defined as the reciprocal of volume resistivity

**contact resistance** in an earth resistance survey, the contribution to the total electrical resistance caused by the interface between the electrodes and the soil. It is difficult to make good electrical contact between a temporarily inserted electrode and dry soil, so this is typically the largest contribution to the overall resistance (Part IV, 1.3)

**curator** a person or organisation responsible for the conservation and management of archaeological evidence by virtue of official or statutory duties (IFA 2001)

**digital elevation model (DEM)** a topographic model of the bare earth that can be manipulated by computer programmes and stored in a grid format

**digital surface model (DSM)** a topographic model of the Earth's surface (including terrain cover such as buildings and vegetation) that can be manipulated by computer programmes

**digital terrain model (DTM)** a topographic model of the bare earth that can be manipulated by computer programmes

**eddy currents** electrical current induced in a conductive feature by a changing magnetic field, which in turn produces a secondary electromagnetic field that can be detected by a geophysical instrument

**electrical skin depth** depth to which the alternating electric current induced by an electromagnetic field will extend into a conductive object or soil. This material property is dependent on the frequency of the incident electromagnetic field and restricts the range of soil conductivity meters when operated at high frequencies over conductive sites.

**fiducial (fiduciary) marker** a marker introduced into a sequence of time-triggered measurements that can be related to a fixed position on the ground. The position of each measurement made by a moving instrument can then be deduced by comparing its time-stamp to that of the closest (in time) fiducial markers.

**fluxgate magnetometer** a solid-state magnetometer that measures the strength of an ambient magnetic field by observing the effect it has on two oppositely wound solenoids. The solenoids are both magnetised by the same alternating electric current and are placed so close together that, in the absence of any external magnetic field the alternating magnetic fields they generate would cancel each other out (*see* Part IV, 1.2).

**fractional conversion** a ratio of magnetic susceptibility before and after laboratory heating of a soil sample to a maximum possible value. High values may be suggestive of occupation processes (burning) that may otherwise be masked through changes in background geology.

**frequency dependence of susceptibility** variation of magnetic susceptibility measured from soil samples in an alternating field at two or more frequencies. High values may indicate the presence of very fine magnetic particles often associated with archaeological settlement activity.

**georeferencing** the process of fixing the location of a field survey grid on the surface of the Earth, thus making it possible to re-established it at a later date. This can be achieved by making measurements to landmarks with known positions or by direct co-registration (often using a GPS system) to a standard map coordinate system such as the Ordnance Survey National Grid.

**geotechnical survey** any subsurface investigation, geophysical or (semi-) invasive, conducted to assist with the technical rather than archaeological aspects of a proposed development or extraction scheme. Such data (eg from an auger survey) may also prove highly useful to archaeological geophysicists.

**grid** *see* **survey grid** and **sub-grid**

**gradiometer** any instrument that records differences in a measured property between two sensors set at a fixed distance apart, rather than the total value of the property measured using a single sensor. This configuration is usually encountered in magnetometers (*see* Part IV, 1.2).

**grey literature** literature that is produced by all levels of government, academics, business and industry, in print and electronic formats, but which is not controlled by commercial publishers. Most geophysical survey reports fall into this category.

**ground-truth** the real physical circumstances as directly measured or observed at the ground surface, or from direct interventions such as coring, test-pitting, trenching or area excavation. Ground-truth data is used to help validate, calibrate and interpret indirect geophysical and remote sensing responses.

**HER** Historic Environment Record

**interpolation** a method for calculating values for new data points in between a discrete set of measured data points. Often used to reduce the blocky appearance of greyscale plots of surveys where the field sample density was relatively sparse. Interpolation does not increase the amount of information in a data-set and is not a substitute for employing a higher sampling density in the field.

**large area** in these guidelines, any area in excess of 20ha

**magnetometer scanning** the informal use of a portable magnetometer to assess magnetic response over a site or area, and/or to locate specific strongly magnetic features. The experienced operator walks across a site, usually at widely spaced intervals (5m +), observing the instrument's output and marking potential anomalies for more detailed investigation. 'Recorded magnetometer scanning' utilises a grid and/or GPS location together with plotting of the instrument signal.

**map regression** the process of using historic mapped information (for example old OS, tithe and estate maps), working backwards in time from the present day, to investigate and reconstruct the past appearance of sites, buildings and landscapes

**pseudo-section** a sequence of earth resistance measurements made along the same surface base-line with different electrode separations and arranged to depict an approximate vertical profile of the variation of electrical resistance with depth (*see* Part IV, 1.3.4)

**reflector** any object with suitable physical properties to reflect an incident GPR signal, often described as point, planar, dipping, linear, complex (diffuse), etc to indicate the likely nature of the causative feature. Hyperbolic responses can be recorded over reflectors of limited cross-section and show characteristic tails, dependent on the velocity of the radar wave, dipping to either side of an apex immediately above the object.

**Section 42 licence** a licence issued in accordance with Section 42 of the Ancient Monuments and Archaeological Areas Act 1979 to those wishing to undertake metal detecting or geophysical surveys over legally protected sites. It currently takes the form of a letter from English Heritage formally authorising the conditional undertaking of such surveys over specified scheduled monuments or other 'protected places'.

**signal-to-noise ratio** used in a general sense to describe the limit of detection for an individual instrument type or technique where the magnitude of response from an underlying feature is no longer discernible above the background noise level

**specification** a written schedule of works required for a particular project (by a curator, planning archaeologist or client) set out in sufficient detail to be quantifiable, implemented and monitored; normally prepared by or agreed with the relevant curator (IFA 2001)

**square array** one of the arrangements of electrodes used for making earth resistance measurements. The four electrodes are positioned at the corners of a square, a configuration particularly suited to four-wheeled cart systems (*see* Part IV, 1.3).

**sub-grid** a square or rectangular block of survey data. Typically an area to be surveyed will be divided up into a mosaic of contiguous squares, each of which will be methodically covered in turn. When transferred to a computer the data-set from each square is initially stored separately and is termed a sub-grid.

**survey grid** the network of control points used to locate the geophysical survey measurements relative to base mapping and/or absolute position on the Earth's surface (*see* Part IV, 1.1)

**time- (depth-) slices** visual representations extracted from a volume GPR data-set showing successive plan views of the variation of reflector energy from the surface to the deepest recorded response (*see* Part IV, 1.4.3)

**thermoremanent magnetisation** a persistent, permanent, magnetisation acquired by certain magnetic minerals after they have been heated above a threshold temperature and then cooled in an ambient magnetic field (such as the Earth's)

**tomography** In the context of geophysics, this term usually describes the process of imaging the subsurface as a sequence of two-dimensional slices. Multiple parallel slices can be measured and combined using a computer to image a volume of the subsurface in three dimensions. An alternative name for electrical sections (Part IV, 1.3.4) is earth resistance tomography (ERT) but GPR can also be considered a tomographic technique.

**travel time** the time required for an incident GPR pulse to pass from the surface to a buried reflector, usually measured in nanoseconds (ns). If the velocity of the radar wave in the soil is known, then the distance to the reflector can be calculated (*see* Part IV, 1.4.3).

**twin electrode (twin probe)** an arrangement of electrodes for making earth resistance measurements that is particularly suited to archaeological geophysics. The two current electrodes are each paired with one of the two potential electrodes, one pair is set into the ground at a fixed reference position while the second is carried on a mobile frame and inserted into the ground wherever a measurement is to be made (*see* Part IV, 1.3).

**written scheme of investigation (WSI)** a detailed scheme for the archaeological evaluation and/or recording of a development site, approved by the Local Authority. In the context of these guidelines. A WSI is equivalent to a **specification** or **project design**.

## Appendix I Related standards, codes and guidance

The only code of practice devoted specifically to geophysical survey in archaeology is one that deals with geophysical data: Armin Schmidt 2002 *Geophysical Data in Archaeology: A Guide to Good Practice*. York: Archaeology Data Service

Readers should also familiarise themselves with: Chris Gaffney, John Gater and Susan Ovenden 2002 *The Use of Geophysical Techniques in Archaeological Evaluations*. Reading: IFA Techn Pap **6**

Codes of practice that otherwise have a bearing on geophysical survey, albeit marginally on its archaeological applications, include:

*British Standards Institution Code of Practice for Site Investigations, BS 5930:* http://www.standardsdirect.org/standards/standards4/StandardsCatalogue24_view_4488.html (1999). A guide to this Code has also been published (2002): http://www.standardsdirect.org/standards/standards4/StandardsCatalogue24_view_26173.html

Darracott, B W and McCann, D M 1986 *Planning Engineering Geophysical Surveys*. London: Geological Society, Engineering Geology Special Publication Number 2.

*Engineering Geophysics: Report by the Geological Society Engineering Group Working Party* 1988. *The Quarterly Journal of Engineering Geology* **21** (3). London: The Geological Society

Building Research Establishment (BRE) 2002 *Optimising Ground Investigation*. Driscoll: BRE. This digest 'informs building and construction professionals who commission ground investigations, especially clients and their advisors who do not themselves have geotechnical qualifications and experience. It aims to raise awareness of the importance of ground investigation for routine projects and provides a summary of best practice'. http://www.brebookshop.com/details.jsp?id=140242

The American Society for Testing and Materials (ASTM: http://www.astm.org/) has produced:

*ASTM D6429-99 Standard Guide for Selecting Surface Geophysical Methods* (which covers forensic and archaeological applications).
*ASTM D6429-99 Standard Guide for using the Surface Ground Penetrating radar method for Subsurface Investigation*

Users of GPR (Part IV, 1.4) should be aware of and abide by the Code of Ethics and the Code of Conduct developed and used by the membership of EuroGPR. The latter is a trade association, open to all GPR practitioners, the goals of which are to promote good practice in the use of GPR for both commercial and academic use throughout Europe, to act as a forum for discussion on topical issues, and to act as a voice for the industry in lobbying European legislative authorities.

If not already members of the IFA, geophysical surveyors should at least abide by its code of conduct (IFA 1986, 1988, revised 2002: http://www.archaeologists.net/).

Contractual arrangements should follow the *ICE Conditions of Contract for Archaeological Investigation* (2004, Thomas Telford Ltd [www.thomastelford.com]). These are the product of a joint working group of the Institution of Civil Engineers (ICE), the Association of Consulting Engineers (ACE), the Civil Engineering Contractors Association (CECA) and the Institute of Field Archaeologists (IFA), and regulate the business relationship between the Employer and the specialist Archaeological Contractor.

Familiarity with the following codes and manuals will also be advantageous:

*Archaeological Investigations Code of Practice for Mineral Operators* 1991. Confederation of British Industry

*The British Archaeologists and Developers Liaison Group Code of Practice* 1991

ACAO 1993 *Model Briefs and Specifications for Archaeological Assessments and Field Evaluations*

Dept of Transport 1993 *Design Manual for Roads and Bridges, Volume 11 Section 3 Part 2: Cultural Heritage*

IFA 1993 *Standard and Guidance for Field Archaeological Evaluations*. Standards in British Archaeology Working Party

## Appendix II Contacts

Advice on geophysical survey can be obtained from the following sources:

### 1 English Heritage Regional Science Advisors:

**North West** (Cheshire, Manchester, former Merseyside, Lancashire and Cumbria)
Sue Stallibrass
Department of Archaeology, Hartley Building, University of Liverpool, Liverpool L69 3GS
telephone: 0151 794 5046
e-mail: sue.stallibrass@liv.ac.uk

**North East** (Northumberland, Durham, Tyne and Wear, Hadrian's Wall)
Jacqui Huntley
Department of Archaeology, University of Durham, South Road, Durham DH1 3LE
telephone/fax: 0191 334 1137
e-mail: j.p.huntley@durham.ac.uk

**Yorkshire and Humber** (Yorkshire and former Humberside)
Andy Hammon
EH York Office, 37 Tanner Row, York YO1 6WP
telephone: 01904 601983
e-mail: andy.hammon@english-heritage.org.uk

**West Midlands** (Herefordshire, Worcestershire, Shropshire, Staffordshire, former west Midlands and Warwickshire)
Lisa Moffett
EH Birmingham Office, 112 Colmore Row, Birmingham B3 3AG
telephone: 0121 625 6875
e-mail: lisa.moffett@english-heritage.org.uk

**East Midlands** (Derbyshire, Leicestershire, Rutland, Lincolnshire, Nottinghamshire, and Northamptonshire)
Jim Williams
EH Northampton Office, 44 Derngate, Northampton NN1 1UH
telephone: 01604 735451
e-mail: jim.williams@english-heritage.org.uk

**East of England** (Bedfordshire, Cambridgeshire, Essex, Hertfordshire, Norfolk and Suffolk)
Jen Heathcote
EH Cambridge Office, Brooklands House, 24 Brooklands Avenue, Cambridge CB2 2BU
telephone: 01223 582759
e-mail: jen.heathcote@english-heritage.org.uk

**South West** (Cornwall, Isles of Scilly, Devon, Dorset, Somerset, Wiltshire and Gloucestershire)
Vanessa Straker
EH Bristol Office, 29 Queen Street, Bristol BS1 4ND
telephone: 0117 975 0689
e-mail: vanessa.straker@english-heritage.org.uk

**South East** (Kent, Surrey, Sussex, Berkshire, Buckinghamshire, Oxfordshire, Hampshire and Isle of Wight)
Dominique de Moulins
Institute of Archaeology, University College London, 31–34 Gordon Square, London WC1H 0PY
telephone: 0207 679 1539
e-mail: d.moulins@ucl.ac.uk

**London**
Currently vacant (April 2008)

Up to date information is available from the following websites:
1. HELM/Managing and Protecting/Delivering advice/Regional science advisers (http://www.helm.org.uk/server/show/category.11227)
2. EH/Research and Conservation/Archaeology and Buildings/Scientific techniques/RSA home (http://www.english-heritage.org.uk/server/show/nav.1273)

### 2 English Heritage Geophysics Team:

Paul Linford
Fort Cumberland, Eastney, Portsmouth PO4 9LD
telephone: 02392 856749
e-mail: paul.linford@english-heritage.org.uk
www: http://www.english-heritage.org.uk/server/show/nav.18391

## Appendix III Useful websites

A comprehensive source for relevant links is at: http://www.brad.ac.uk/acad/archsci/subject/archpros.htm

The links provided below are intended as an informal listing of current (2008) websites that may of interest to readers. English Heritage does not accept any responsibility for the accuracy of these websites or their contents, and inclusion on the list does not mean that English Heritage has given any approval or accreditation to the company or individual concerned. As time goes on, this listing will be updated on the web version of this document (see www.english-heritage.org.uk)

### Contractors/consultants

www.archaeologicalgeophysics.co.uk

http://apss.soton.ac.uk

www.arch.wyjs.org.uk

www.archaeophysica.co.uk

www.arrowgeophysics.co.uk

www.dur.ac.uk/archaeological.services/geophysical_survey/

www.shef.ac.uk/arcus/

www.arch-ant.bham.ac.uk/bufau/

www.cambrian-archaeology.co.uk

www.earthsound.ie

www.geophysics.co.uk

www.le.ac.uk/ulas/services/geophysical.html

www.metsurveys.com

www.northantsarchaeology.co.uk

http://dspace.dial.pipex.com/town/terrace/ld36/

www.geophysical.biz

www.targetgeophysics.ie

www.archaeological-surveys.co.uk

www.apac.ltd.uk

www.arcauk.com/geophys.html

www.archaeologists.tv

www.archaeological-services.co.uk

www.contextone.co.uk/geophysics.htm

www.dvasltd.com

www.nparchaeology.co.uk

www.gsbprospection.com

www.geofizz,net

www.geologyuk.com

www.sitescan-uk.com

www.souterrain.biz

www.stratascan.co.uk

www.terradat.co.uk

www.terranova.ltd.uk

www.testconsult.co.uk

www.wessexarch.co.uk

### Non-Destructive Testing

www.gbg.co.uk

www.aperio.co.uk

### Manufacturers

#### Magnetometers

www.geometrics.com

www.bartington.com

www.geoscan-research.co.uk

www.scintrexltd.com

www.gemsys.ca/

#### EM

www.geonics.com

www.iris-instruments.com

#### GPR

www.sensoft.ca/

www.utslelectronics.co.uk

www.malags.com

www.era.co.uk

#### Earth resistance

www.cix.co.uk/~archaeology/cia/resistivity/resist.htm

www.trsystem.demon.co.uk/html/archaeology_and_other_products.html

www.geoscan-research.co.uk

### Rentals/supplies

www.georentals.co.uk

www.allied-associates.co.uk

### Software

Geoplot (Geoscan Research) www.geoscan-research.co.uk/page9.html

ArcheoSurveyor (DW Consulting) www.dwconsulting.nl/archeosurveyor.htm

Geosoft www.geosoft.com

Snuffler (basic but free) www.homeusers.prestel.co.uk/aspen/sussex/snuffler.html

Surfer (surface plotting) www.goldensoftware.com

### Miscellaneous

English Heritage Geophysical Survey Database: http://sdb.eng-h.gov.uk

North American Database of Archaeological Geophysics (with extensive links): http://www.cast.uark.edu/nadag/

ADS Guidance. Geophysical Data in Archaeology: A Guide to Good Practice: http://ads.ahds.ac.uk/project/goodguides/geophys/

Journal: Archaeological Prospection: http://www3.interscience.wiley.com/cgi-bin/jhome/15126

International Society for Archaeological Prospection: http://archprospection.org/

Environmental and Industrial Geophysics Group (EIGG): http://www.geolsoc.org.uk/template.cfm?name=geogroup12

EIGG Test Site: http://www.le.ac.uk/gl/iah/research/EIGG/eigghp.html

Butser (test site available?): http://www.butser.org.uk/

NERC Geophysical Equipment Facility: http://gef.nerc.ac.uk/

GPR-SLICE software and GPR case studies: www.gpr-survey.com

GPR case study (Petra): http://e-tiquity.saa.org/~etiquity/title1.html

Archaeological Investigations Project: http://csweb.bournemouth.ac.uk/aip/aipintro.htm

European GPR Association: http://www.eurogpr.org/

## Appendix IV List of consultees

### Organisations

Association of Local Government Archaeological Officers (ALGAO)

Council for British Archaeology (CBA)

English Heritage (Regional Science Advisors; EH Standards Group)

Institute of Field Archaeologists (IFA)

Oxford Archaeology

Wessex Archaeology

### Individuals

Mr T Archer (Arrow Geophysics)

Mr P Barker (Stratascan)

Mr G Bartington (Bartington Instruments)

Mr A Bartlett (Bartlett-Clark Consultancy)

Mr N Bell (Allied Associates Geophysical Ltd)

Mr A Boucher (Hereford City and County Archaeological Trust Ltd)

Mr A Butler (Northamptonshire Archaeology)

Dr M Canti (English Heritage)

Mr P Cheetham (University of Bournemouth)

Dr K Hamilton (Norfolk Landscape Archaeology)

Mr D Hale (University of Durham)

Dr C Gaffney (University of Bradford)

Mr J Gale (University of Bournemouth)

Dr J Gater (Geophysical Surveys of Bradford)

Mr D Gurney (Norfolk Landscape Archaeology)

Mr A Johnson (Oxford Archaeotechnics)

Dr R Jones (University of Glasgow)

Dr J Last (English Heritage)

Dr J Leckebusch (Terra International)

Mr C Leech (Geomatrix Earth Science)

Mr J Lyall (Landscape Research Centre)

Mr A Oswald (English Heritage)

Mr M Papworth (National Trust)

Dr J Reynolds (Reynolds Geosciences)

Mrs A Roseveare (ArchaeoPhysica)

Mr M Roseveare (ArchaeoPhysica)

Bronwen Russell (University of Bournemouth)

Mr D Sabin (Archaeological Surveys)

Dr A Schmidt (University of Bradford)

Ms E Utsi (Utsi Electronics)

Dr R Walker (Geoscan Research)

Mr A Webb (Archaeological Services, WYAS)

**Contributors**
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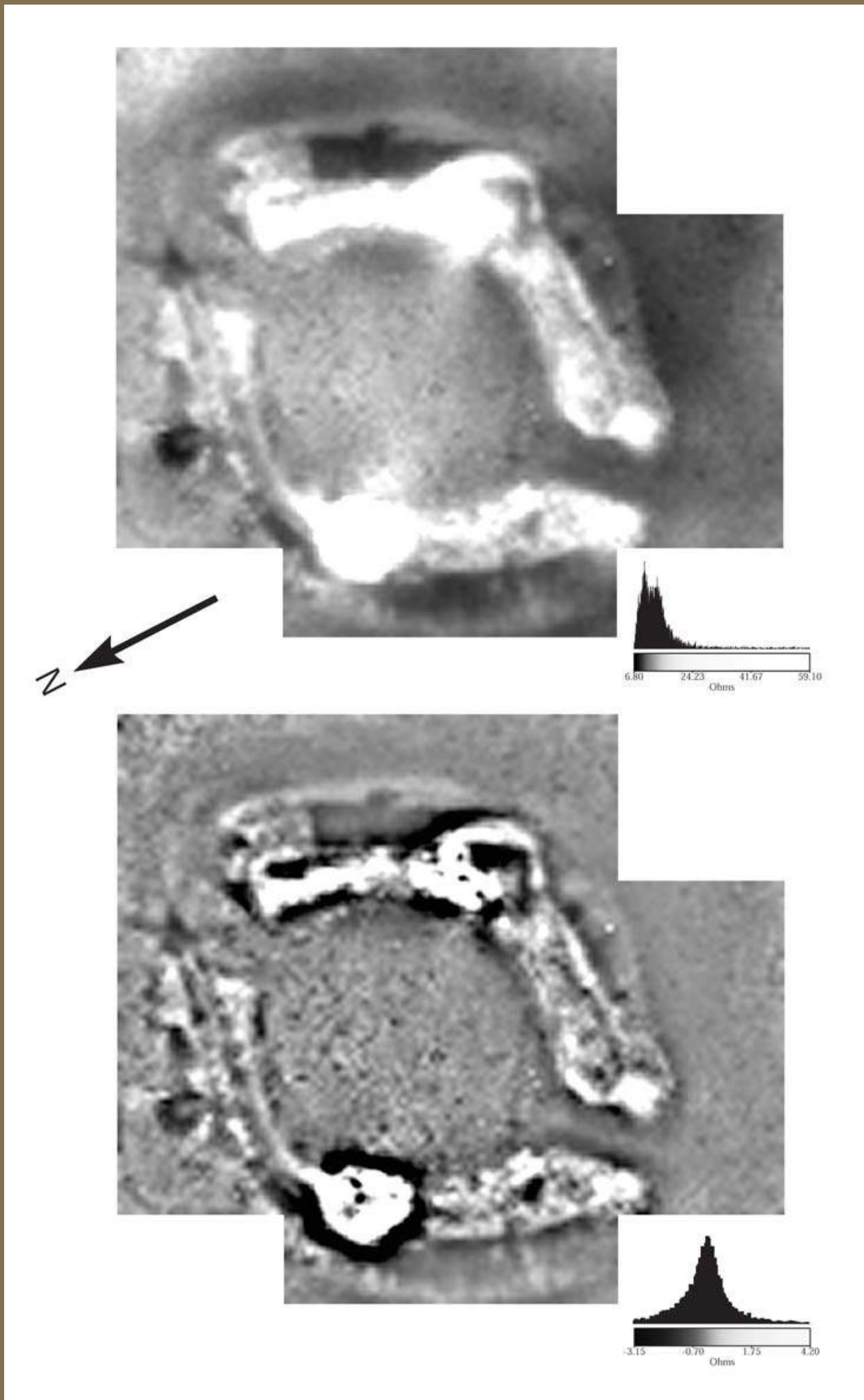


**Back cover caption:** (above) Greyscale plots of an earth resistance survey over the Roman amphitheatre at Richborough in Kent. The upper plot shows the unprocessed data whilst the lower depicts the same data after high pass filtering to emphasise internal details of the amphitheatre's structure.

**Front cover caption:** Greyscale plot of a portion of a caesium magnetometer survey over an Iron Age settlement at Flint Farm in Hampshire (left) compared with a photograph of the same area during excavation (right).

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