CAA 97

Twenty five years of archaeological prospection

A. Aspinall and J.G.B. Haigh

Abstract

Much of the basic instrumentation in current use in archaeological geophysics had already been developed by 1972. The next fifteen years were a period of consolidation and adaptation for general use. The last ten years, up to 1997, have seen the introduction of new methods of field investigation, such as ground-penetrating radar and other electromagnetic methods. In Britain, partly as a result of legislation on land utilisation, there has been an explosion of archaeological interest in geophysical survey. The improvements in instrumentation have been paralleled by developments in data handling, presentation and interpretation. The problems of the 1970s were mainly concerned with the visualisation of data, allowing only minimal interpretation. In the 1980s, as increasing computer power became available, methods of data enhancement were introduced. In recent years attention has been focused on reconstructing the physical objects which give rise to the observed data, only a short step from direct archaeological interpretation.The future prospects are towards the interlinked development of instrumentation and interpretative methodology.

1 Introduction - the state of development twenty-five years ago

To discuss what has happened in geophysical prospection for archaeology over the last twenty-five years, we must first look back to the "state of the art" in 1972, at the start of the period. At that time the only journal devoted exclusively to the subject was *Prospezioni Archeologiche*, which had been founded in 1966 under the motivation of Richard Linington for the Lerici Foundation in Rome. Since it ceased publication in 1984, it is opportune to look at the contents of the issue for 1972-73, where we discover that many of the articles still look reasonably up-to-date! The paper by Linington (1972) himself, for instance, still remains the classic mathematical description of the magnetic field observed in archaeological prospection. Clark and Haddon-Reece (1972) set out their design for an automatic recording system based on fluxgate magnetometers, well ahead of the time when similar systems would be adopted by the majority of workers.

Indeed, most of the basic developments in hardware had already been made, and have been well documented by Clark (1990). In 1946 Richard Atkinson carried out the first significant earth resistance survey, using a "Megger" Earth Tester and a Wenner array (Atkinson, 1963). Tony Clark followed in 1956 with a dedicated instrument, the Martin-Clark meter, which became the standard instrument for use with a switched Wenner array; essentially it used a potentiometric backing-off procedure to give a "null" balance and was, therefore, slow in use. In 1958 Martin Aitken and Teddy Hall developed the first proton magnetometer (or gradiometer) for archaeological use; with a sensitivity down to 1 nT (nanoTesla), it was again slow in operation, taking up to one minute for verified readings.

The success of these prototype instruments led to developments which were effectively completed by 1972. The "direct-reading" earth resistance meter gave an analogue output proportional to earth resistance in all but the most exacting soil conditions. The prototype alkali-vapour magnetometer was in place, giving a potential sensitivity 100 times better than the proton magnetometer, but with depressing handling problems. At Oxford John Aldred had developed the first fluxgate gradiometer, which rapidly led to more convenient forms from Frank Philpott at Plessey and Geoff Bartington at Littlemore.

The possibility of simultaneous measurement of magnetic and conductive properties, well established in geology, entered the province of archaeology through the use of the metal detector principle and the development of phase-sensitive amplifiers. The SCM (soil conductivity meter, better known as the Banjo) became the SSM when it was realised that, at its operational frequency, it was measuring soil susceptibility! The PIM (pulsed induction meter) also came into use without a full understanding of its operational principles, which involve quadrature susceptibility or magnetic viscosity. Ground-penetrating radar (GPR) and seismic methods were in the wings and developments in Japan and the USA were reported around 1972, but as yet there were no significant contributions to archaeology.

Innovation in hardware was lively. The spiked wheel resistance system and continuous analogue recording from both resistance and magnetic surveys with potentiometric distance transducers led to the prolific production of *x-y* plots as linear records. Otherwise data were mainly recorded by hand for later processing, usually in a grid format. It is useful to examine what techniques for data processing were available in the early 1970s. As in other aspects of archaeological prospection, Irwin Scollar led the way by using the computer facility at Bonn to present magnetometer data in a dot-density format, the preferred style for most data for years afterwards (Scollar, 1966). Others, with more modest means, devised simple semi-conductor matrix image displays to produce intensity plots proportional to the magnitude of the data, photographed them, and pieced them together appropriately, with variable results .

The computing facilities available to the majority of workers were fairly primitive. Some were employing mini-computers, usually designated primarily for other purposes, with miscellaneous display and printer facilities, to produce plots of large-scale surveys. Others were using limited central computing resources to simulate patterns of intensity on line printers. Data treatment was at an elementary level, usually in terms of simple spatial filters, but Scollar was already utilising the Bonn computer to investigate more sophisticated procedures (Scollar, 1966). It is in the recording and treatment of data that the most obvious and far-reaching advances have been made over the last quarter century, enabled by the steadily increasing power of micro-computers.

2 Advances in field instrumentation

What has changed over the last twenty-five years? In terms of hardware, perhaps the most significant development was the fitting of digital logging systems to existing equipment. Thus the early "Bradphys" resistance meter in 1985 evolved into the Geoscan RM4 with a DL110 data logger, capable of logging 1000 readings before it becomes necessary to download the data into a more permanent store (Clark, 1990, p45). There have been corresponding developments with magnetometers; for instance, the Geoscan FM18 fluxgate gradiometer has a built-in logger with a capacity of 3000 readings (Clark, 1990, p17). Alternative data-logging systems appeared, originally developed as hand-held organisers. Transfer of readings to portable computers in the field rapidly became the norm, allowing raw data to be turned into visible results within minutes of recording.

Nowadays field-based systems are capable of processing vast quantities of data; the Geoscan RM15 resistance meter can store 30000 readings, and the FM36 magnetometer 16000 readings. These large capacities are the result of the rapid developments in micro-electronics and mass storage over the last few years. They both represent more data than field teams could produce in a working day, when the instrumentation still relied on the manual intervention of the operator to allow each reading to be recorded. The rapid turn-round of data has led to calls for more rapid acquisition of readings. The improved recording rate could be used simply to extend the area of survey, an important consideration in Britain, where there is a statutory requirement to examine all archaeologically sensitive land prior to its development. Otherwise it may be used to reduce the sampling interval, thereby increasing the survey intensity and improving the detail visible in the results. To satisfy these requirements, various mobile systems for earth resistance survey have appeared (Hesse *et al.*, 1986).

Another important development is the switched system of many electrical probes, slaved to the logger through a multiplexer, allowing the rapid assessment of thirty or more data values, with a variety of inter-probe spacings and array configurations (Griffiths and Turnbull, 1985). The resulting data-bank offers a new potential for interpretative procedures (Szymanski and Tsourlos, 1993). Of course, there are logistical problems in transferring the whole multi-probe assembly to a new location ready for the next scan, but their solution is a matter of efficiency in field procedure.

The current range of fluxgate and caesium-vapour magnetometers permits reliable sampling to take place within a fraction of second (Becker, 1996). When allowance is made for the movement of instruments and survey markers, it is feasible to acquire around 40000 readings in the course of a day's work of 10 to 12 hours. Using very close sampling (0.5 m or 0.25 m), it is possible to obtain detailed views of magnetic anomalies which are amenable to more sophisticated techniques of interpretation.

What alternative hardware techniques have been developed? Low frequency (up to 50 kHz) electromagnetic systems have shown limited innovation in the past 10 years. In France, however, Alain Tabbagh has developed the so-called Slingram (twin coil and boom) instrument (Hesse *et al.*, 1986). There is growing appreciation of the significance of the phase of the returned signal as a means of distinguishing between the conducting and magnetic features, although the complications of the viscous component in the magnetic response remain a problem.

There is also the question of depth of survey, a problem which has persisted over many years and which may ultimately prove to be insoluble, in terms of desired accuracy and reliability. Wider coil separation gives greater depth of penetration but poorer resolution. In Britain, the Bartington electromagnetic system, reminiscent of a metal detector, but with the facility for dual frequency operation, is now used extensively for studies of top-soil magnetic susceptibility (Clark, 1990).

The study of vertical sections, leading to the possibility of 3-dimensional examination of a site, has perhaps found its most significant stimulation in the past twenty years through developments in GPR (Malagodi *et al.*, 1996). By selective use of central frequencies from 100 MHz to 1 GHz, it is now feasible to penetrate to depths of many metres of soil and to make detailed studies behind solid walls. To the non-specialist, however, visualisation of anything but the simplest of features presents considerable difficulties. The complex manner in which heterogeneous media and their interfaces influence the velocity of propagation and reflection characteristics of electromagnetic waves leads to processing problems which have still not been solved. The most attractive visual presentation has been realised through the use of close-spaced vertical scans from which "horizontal" sections (time slices) have been produced. Such techniques, however, do not solve the problems of complex raw data and their resolution into discrete features.

Other vertical sections have been produced following the use of multi-probe systems in earth resistance survey; they are often presented as simple or tomographic "pseudo-sections". They are normally of limited resolution and reflect the complexity of resistance anomalies resulting from 3-dimensional buried features. In principle, it should also be possible to ascertain some information about the depth of features by using multi-sensor magnetometers, with an array of sensors set at different heights. In practice, the sheer complexity of features at the majority of archaeological sites has so far prevented anything more than the most rudimentary three-dimensional information being obtained.

3 Advances in data processing

In terms of data processing and presentation, the past quarter century can be divided roughly into three overlapping decades, corresponding to three recognised levels of image processing. This is the case for the majority of people, but there were always some workers with access to advanced equipment who were able to make pioneering developments well ahead of the rest of the field.

During the 1970s surveyors were mainly concerned with the *visualisation* of data, or visual presentation, to give a visible form to its essential features with whatever computing equipment was available. As computer power became more affordable through the 1980s, effort was concentrated on the *enhancement* of the visible image, to make the significant features stand out more clearly and to separate different classes of feature. In the 1990s, as constraints on computer resources steadily disappear, people are able to concentrate on the *reconstruction* of the physical objects which give rise to the measured signals, and which they hope correspond to the archaeological features of interest.

4 Data visualisation

The importance of *dot-density* patterns in the development of area survey has already been mentioned; they were among the most successful of the techniques of data presentation during the early part of this period (Aspinall and Haigh, 1988). Their importance still continues to the present day, although in a somewhat changed context; when a printer is used to obtain a hard copy of a grey-scale image, the printing software interprets the different intensities as patterns of dots. The procedure is partly hidden from the user, but it may still be necessary to make an informed selection from various "dithering" techniques. An incidental advantage is that the images are effectively "screened" and ready for publication. True solid shades of grey can be produced only by the very latest laser printers, the most expensive in terms of capital and running costs.

When images are displayed on a computer monitor, it is usually more attractive to represent intensities in terms of a *grey-scale*. The appearance of the results greatly depends on the quality of the graphics card, particularly on the number of grey levels available (2, 4, 16, 64, or 256). In the early days workers had to be satisfied with fairly coarse results, but most modern computers, including the "lap tops" likely to be used during field surveys, are available with graphics cards of high quality.

Contour diagrams were popular around 1980, as pen plotters became available on the majority of central computer systems (Haigh and Kelly, 1987). They provide a very accurate way to display data, but they can be rather confusing for the non-specialist and have largely been displaced by other techniques. It is easy to see the regions of rapid change, reflected in the density of the contour curves, but it is harder to distinguish "peaks" from "troughs", unless some form of colour coding is introduced.

Colour displays became generally available on micro-computers from the mid-1980s onwards. The discreet use of colour can be a useful way of emphasising the contrast in specific regions of the plan, but gaudy presentations are liable to distract attention from the underlying data. There are some situations in which the use of colour can be particularly recommended, for instance, in distinguishing between positive and negative readings in a magnetometer survey. It is worth noting that a coloured plan is equivalent to a contour diagram, since the emphasised boundary between adjacent regions of contrasting colours constitutes a contour curve.

There is some enthusiastic support for viewing data by a *3-dimensional construction* of the plotted surface. This can be achieved quite simply through a fishnet or wire-frame diagram, but the availability of 3D graphics on the more powerful modern computers allows it to be shown more realistically as a lit surface. Although the latter results can be very impressive, especially in their ability to distinguish between peaks and troughs, they can sometimes be confusing, and the present authors generally prefer a good, clear 2-dimensional plan (grey-scale, linear contour, or colour map) as an accurate method to represent the data (Aspinall and Haigh, 1988).

A great incentive for improved methods of data visualisation has come from the advent of *automatic data loggers*, allowing large quantities of data to be transferred quickly and accurately to a computer system. The provision of reliable, high-resolution data enables a reliable picture of the results to be obtained. Furthermore, using the power of modern portable computers, the surveyors can assess the success of their work, even as the survey is proceeding.

5 Image enhancement

It is natural to apply the standard techniques of image processing in an attempt to improve the desired features of the visualisation and to suppress those which seem less desirable. *Contrast stretching* and *histogram manipulation* are the most fundamental of such techniques, enabling the best use to be made of whatever range of grey or colour levels is available. It should be ensured that the top level matches the maximum reading, and the bottom level the minimum, and that there is a good balance of readings over the intermediate levels.

Spatial filtering, which was very popular in the late 1970s and early 1980s, involves overlapping the data with a suitable mask in order to emphasise certain aspects of the image. Simple examples include sharpening filters to emphasise the edges of features, and smoothing filters to suppress noise and small features. More sophisticated low-pass filters can emphasise extended features at the expense of smaller ones; similarly high-pass filters emphasise compact (possibly archaeological) features at the expense of more extended (geological) ones (Cheetham et al., 1991). Closely related to sharpening filters are a more specialised group for *edge detection*, often used as a first step towards automatic interpretation of images.

One particularly important concern is *noise suppression.* This can be achieved by means of smoothing filters, as described in the last paragraph, but may result in the blurring of edges. Geophysical data often suffer from "salt and pepper" noise where, for a variety of reasons, the instrument is liable to give occasional anomalous readings at random intervals. It is preferable to isolate such readings on the basis of a statistical comparison with their neighbours, and to replace them with suitable interpolated values.

Once the image has been cleaned up, attention can be directed to the details of the display. It is common to represent each reading as a grey square of appropriate intensity at the relevant position on the plan. An assemblage of *grey squares* often has a "blocky" appearance, through which it is not easy to discern the underlying shape of a feature. Some method of interpolation is desirable, to give smoother edges to the features. *Bilinear interpolation* is an obvious answer, and has long been used, particularly in the construction of fishnet diagrams and contour maps. It has a number of disadvantages, especially in its tendency to reduce contrast in the highlights, and a more sophisticated technique may be called for. *Bicubic interpolation* is more difficult to implement reliably, but has proved to be a practical technique for modern computers and to be capable of overcoming many of the disadvantages of bilinear interpolation.

Although an assemblage of survey readings has a general appearance which is superficially similar to a digital image, some essential differences have to be taken into account. The physical processes underlying geophysical survey are usually more complicated than those involved in the formation of a photographic image; the error distribution is of a different nature; whereas a digital image normally consists of a complete rectangular array of values, with at most a small number of missing pixels, geophysical results are restricted by the shape of the accessible region of survey, and may have large numbers of missing values. For all these reasons, standard imaging procedures should not be applied uncritically to survey data.

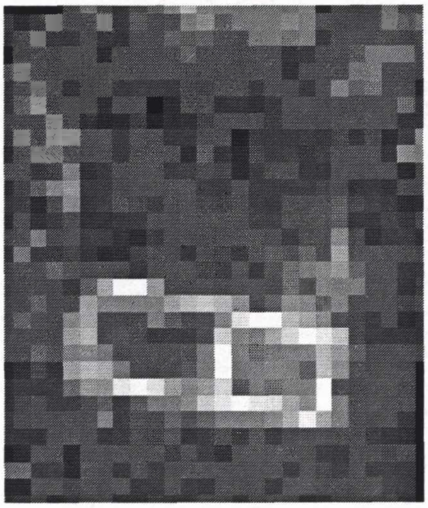

Figure 1: The foundations of a small chapel revealed by twin-probe resistance survey. The interval between readings is 1 m; regions of high resistance are shown as light squares.

One particular problem with geophysical survey concerns "aliasing", which occurs when a detected feature has a horizontal dimension smaller than the sampling interval. The feature may then appear as a series of disjointed items, several sampling intervals apart. Figure 1 is a grey-scale representation of a twin-probe resistance survey, revealing the foundations of a small chapel; the readings are at intervals of 1 m. The walls are obviously continuous features running at a small angle to the direction of survey, but have been revealed as disconnected horizontal strips. In Figure 2 the data have been enhanced by bicubic interpolation; this gives a better impression of the continuous nature of the walls, but still presents them as series of connected horizontal segments, rather than truly linear features.

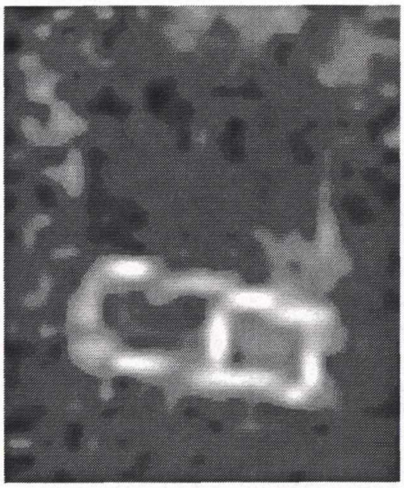

Figure 2: The data of Figure 1, displayed with bicubic interpolation.

The only certain way to avoid aliasing is to ensure that the sampling interval is smaller than the dimensions of the smallest feature that can be detected by the equipment. Unfortunately it is difficult to make an accurate frequency analysis of the response of most geophysical instruments, and hence to predict the optimal sampling interval. This provides a sound reason for the use of modern fast data loggers, since they permit sampling intervals to be set at values smaller than the resolution of the instruments.

6 Physical reconstruction using inverse data methods

Back in the early 1980s numerical procedures based on the fast *Fourier transform* were regarded with some awe. Any realistic calculation required a large amount of computer time, even on powerful machines, and you were often recommended to buy specialist processors costing thousands of pounds. Nowadays it takes only a few seconds to run the same calculation on a modern personal computer and, when an intensive application demands results in a fraction of a second, specialist processors can be purchased for a few hundred pounds each.

At a basic level, Fourier transforms provide alternative filters in frequency space to the spatial filters described in the last section; whether it is preferable to use a spatial filter or its equivalent in frequency space depends upon the size and nature of the filter (Cheetham *et al.*, 1991). At a deeper level, they can be used to construct an inverse for any linear process which is believed to have degraded the quality of the perceived image. The inverse filter may be applied to the observed image in the hope of *restoring* it to its original quality, or of *reconstructing* the ideal image. For instance, the signal (or spread function) from a small subsurface magnetic source, effectively a dipole induced by the earth's field, has the general appearance shown in Fig. 3, with an intense positive lobe to the south of the source and a diffuse negative lobe to the north (Linington, 1972). The precise form of the spread function depends on geographical location on the earth's surface; the form shown in Figure 3 is typical of British latitudes. The superposition of spread functions from a collection of such sources gives rise to the characteristic positive and negative pattern of magnetometer readings. In order to reconstruct the archaeological sources of the observed signals, we might attempt to calculate a frequency filter which inverts the effect of the spread function.

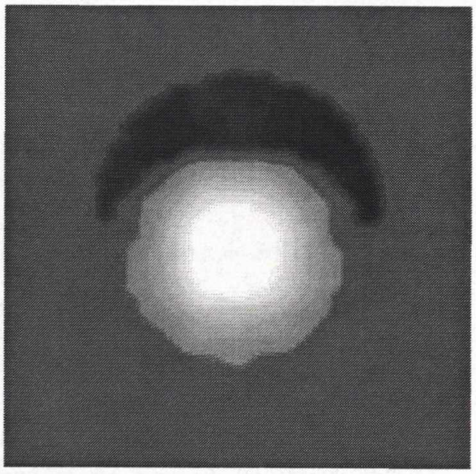

Figure 3: The spread of gradiometer readings over a small induced magnetic dipole in British latitudes. Positive anomalies are shown as light regions, negative anomalies as dark. The diagram represents an area about 10 m square.

Now that sufficient computing power is readily available to apply Fourier methods to reconstruction problems in archaeological magnetometry, it is found that they do not generally work. The major difficulties are that Fourier methods require a complete rectangular image to be available, not often the case in archaeological geophysics, and that they tend to amplify any noise within the data. The distribution of errors in magnetometer data is of such a nature that a reconstruction based on an inverse spread function is entirely dominated by noise, without any discernible pattern of features. Although there are some techniques, notably the Wiener filter, which are designed to reduce the problem of noise, they do not give very useful results in this instance.

In order to overcome these difficulties, it is necessary to turn to more complicated inverse data methods. Here the physical situation is modelled for features of specified shape and the parameters defining the features are adjusted, until an optimum fit to the observed data is achieved. In order to obtain sensible results, it is generally necessary to make some *a priori* assumptions about the nature of the underlying features, so that *constrained inversion* is achieved, taking the defined prerequisites into account. Statisticians prefer to describe the prerequisites as a *prior* distribution for the model, and the constrained optimisation as leading to a *posterior* distribution, when the procedure is known as a Bayesian method. These techniques have been successful in reconstructing physical features (Allum *et al.*, 1995 and 1996), although they have yet to be adapted to a form suitable for the majority of magnetometer surveys.

A crucial advantage of inverse data methods (or Bayesian methods) is that they are not confined to any particular shape of data set; the data need not conform to a rectangular array, as they must for Fourier techniques. The points in the reconstruction set need not match the locations of those in the data set. Provided that the prior distribution is defined appropriately, for instance, it is possible to calculate many more reconstructed points than data points, so providing an automatic form of interpolation. This is particular useful when features are expected to have smoothly curving boundaries.

There have been similar theoretical advances in connection with multi-probe resistance surveys (Szymanski and Tsourlos, 1993). The calculations tend to be much heavier than those for magnetometry, since it necessary to estimate the flow of electric current through all the surrounding soil, rather than use a standard spread function for each reconstructed point. In order to limit the calculation to a realistic size, the reconstruction has to be restricted to a "pseudo-section" through the features of interest, rather than fully extended into three dimensions. Nevertheless Szymanski and Tsourlos have had considerable success in accurately locating a variety of features within the cross-section, using any of the standard probe arrangements. Furthermore, they have issued a practical computer code which is capable of analysing results as quickly as a competent field team should be able to collect them.

7 Future prospects

Clearly the most conspicuous development over the last few years has been in GPR, and it is likely that such systems will continue to develop. At high frequencies the use of "one-shot" and frequency-modulated radar systems is attractive. It is also important that more attention should be paid to electromagnetic systems at low frequencies, in order to exploit the simultaneous measurement of conductive and magnetic properties without the need to use probes.

These modern instruments tend to be expensive to purchase and to require high technical competence for their operation. They produce huge amounts of data; even by modern standards, sophisticated software and massive computing resources are required to obtain the best results from them. More conventional instruments are likely to provide the basis for the majority of archaeological survey for some time to come. Their performance will be improved by the multiplexing of simultaneous readings, and by analytical software which can be supported on the modern range of portable "lap-top" computers.

We have discussed how multi-probe resistance surveys can be used, not only to indicate the horizontal location of features, but also to give an accurate estimate of their depth below the ground surface. There can be little doubt that these techniques will be improved and refined over the next few years. Magnetometry will continue to develop through the increasing portability of stable, sensitive instruments; again the use of multiple sampling, probably through an array of sensors at different heights, will broaden the data base. In the longer term the development of high-temperature superconductors should lead to a new range of more sensitive and more versatile magnetometers.

The last few years have been marked by concurrent developments in both the field instrumentation and in the data processing necessary to analyse the readings. It is important that this situation should continue. There is now a great opportunity to produce new instruments which are designed not merely to record more data more rapidly, but to provide results which can be analysed in response to specific tasks. The multi-probe resistance systems and the multi-sensor magnetometer arrays make some initial steps along this path.

The question then arises as to how archaeologists intend to take into account these new sources of more precise and more reliable information. It cannot be satisfactory simply to say that they will provide a better starting point for traditional excavation techniques. Archaeological methodology as a whole must be updated to accommodate the improved sources of geophysical data in a wider and more versatile information system.

During the period when they were preparing this paper, the authors were saddened by news of the untimely death of Tony Clark. The earlier references to his work are a clear indication of the signal contribution he has made to the development of archaeological geophysics. The authors wish to take this opportunity to record their appreciation of his life and work.

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Contact details

Department of Archaeological Sciences
University of Bradford
Bradford
A. Aspinall
West Yorkshire BD7 1DP
UK

Department of Mathematics
University of Bradford
Bradford
J.G.B. Haigh
West Yorkshire BD7 1DP
UK
J.G.B.Haigh@bradford.ac.uk