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A review of techniques for the graphical display of geophysical data

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19.1 Introduction

For over a quarter of a century the University of Bradford has been prominent in the development of geophysical methods for archaeological survey, using a wide variety of techniques. Measurements of earth resistance have been made with a number of different probe configurations and, indeed, a design originating from the University of Bradford provided the standard resistance meter in British archaeology over a good number of years. Fluxgate and proton precession magnetometers of a variety of designs have been employed, and there has been some experimental investigation of more general techniques (Aspinall & Lynam 1970; Aspinall & Walker 1975). Results from the application of these methods have appeared in occasional publications from the School of Archaeological Sciences (Pocock 1982, Pocock 1983).

Once a particular instrument has been successfully employed in the field, the emphasis quickly changes from the physical problem of actually taking the readings to a computational one of assessing the significance of the values obtained. In general, the problem is one of presenting the data on a site plan in such a manner that the important features of the survey become apparent. In the early years, the presentation had to be organised by hand; the most common technique was to write the data values on to gridded paper and then to connect points with similar values, either by drawing curves around them, or by colouring the grid cells according to their values. Thus hand-drawn contour plots and simple false-colour diagrams were among the early methods of data display.

It soon became apparent that the amount of data was growing too large to be analysed conveniently through hand-drawings and, as the early computer graphics became available, experiments were made with new methods of display. Among the

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first methods tried were dot-density patterns and isometric or perspective views of wire-frame models. Although the wire-frame models have been revived from time to time, they have never found lasting favour in the School of Archaeological Sciences. On the other hand, the dot-density patterns, in several different forms, have remained in favour; they and contour plots provide the two principal means of display of geophysical data employed by the School at the present time.

A good method of presentation should provide a clear but objective view of the data, enabling the user to get a general impression of the overall site, while permitting the examination of any small but significant details that may have been revealed, possibly at varying levels of intensity. It should be available fairly swiftly as a screen display, but yet be capable of being converted into an accurate and inexpensive hard copy. As it is likely that no one method can meet all these requirements, users may prefer to employ some combination of available methods.

Three of the methods mentioned earlier—wire-frame models, dot-density patterns, and contour plots—are discussed in the following sections, together with the possibilities for grey-scale diagrams and false-colour models using the high-quality graphics, now becoming readily available on modern microcomputers. One section is devoted to the authors' experience with filtering techniques for enhancing the data, and to a discussion of the proper usage of such enhancement techniques.

19.2 Isometric or perspective plots

As mentioned in section 19.1, isometric plots were tried as a display method almost as soon as suitable hardware, initially a pen plotter, became available. In such a plot each reading is taken as a z-coordinate, so that the complete set of data forms a surface above the xy-plane in which the readings were taken. The surface is then drawn as though viewed from a position which makes the z-axis more or less parallel to the vertical in the display surface, with the x- and y-axes at suitable angles. The recent trend has been to employ a photogrammetric projection, so that the diagram appears in full perspective. It is usual to represent the surface as a wire-frame model, by drawing vectors between adjacent data points. The diagram can be readily constructed, either by vector graphics on screen or by a pen plotter. When a continuous reading magnetometer is employed, a cruder version can be produced by stacking the x-y plots along successive transects behind one another; a simple example of such a diagram is shown in Fig. 19.1.

A wire-frame plot of this type can give a very clear overview of the data, with a strong impression of the relationship between the main features, and is often appreciated by someone who lacks experience in the assessment of continuous spatial data. Among its disadvantages is the fact that a prominent feature may hide weaker features. Although this problem may be overcome by allowing the user to change the apparent point-of-view, it may still make it impossible to obtain a general impression of all the data at the same time.

Another disadvantage is that, since the magnitude of the reading is indicated by a vertical displacement from a base plane, it is difficult to ascertain the exact horizontal location of the reading. Although it is possible to devise ways to circumvent this problem, the difficulty remains that this form of display does not provide a working plan of the site. In fact, the greater the versatility of the program in providing a realistic perspective view, the further the display differs from a working plan.
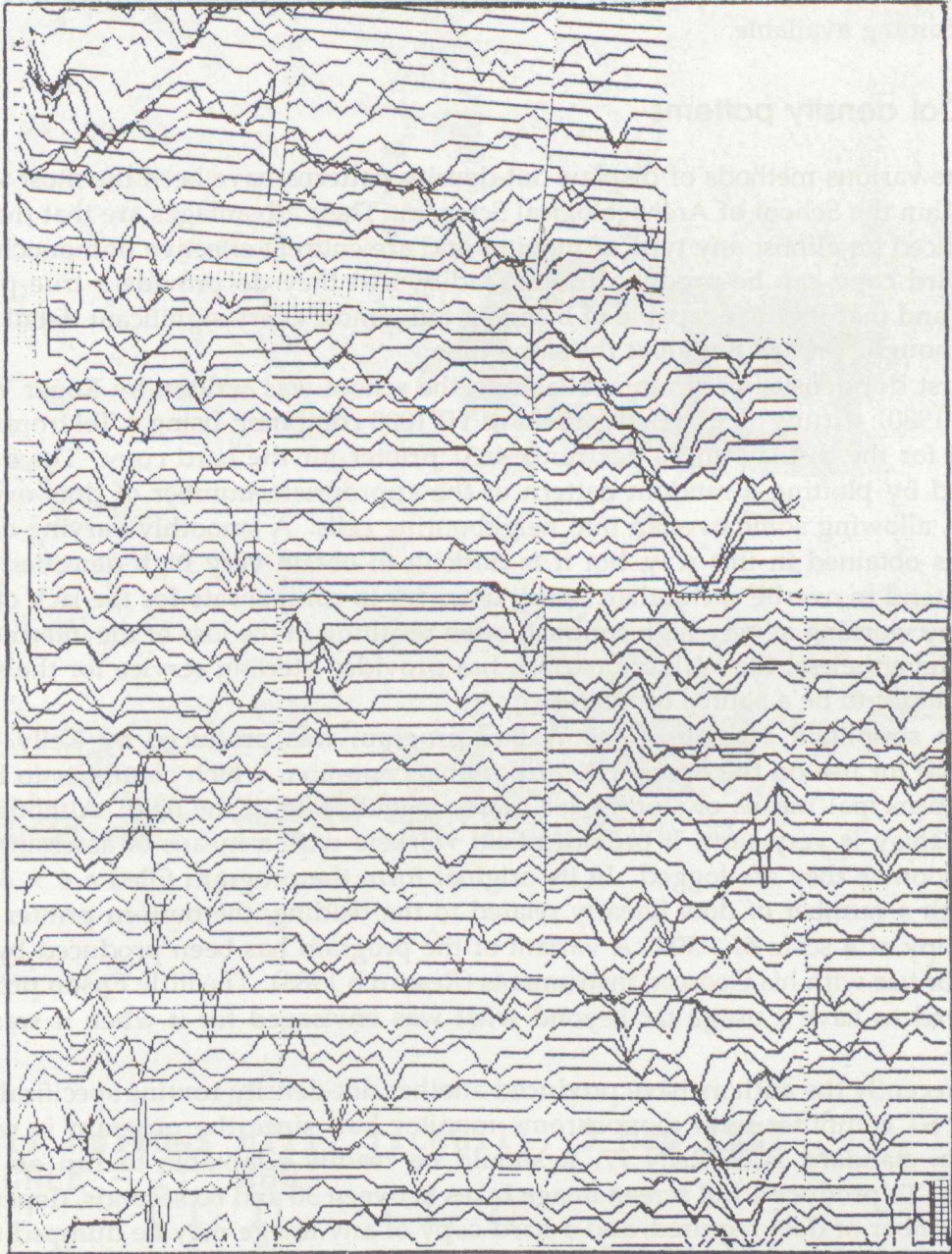
Figure 19.1: A set of x-y plots stacked to give the impression of a continuous surface, with features represented by peaks and valleys. The data, from a magnetometer survey at Greenlands, North Humberside, are displayed using Geoplot software from Geoscan Research.

For these reasons the wireframe model has never found great acceptance as a useful method for displaying geophysical data at the University of Bradford. In any event it is probably about to be superseded by some of the newer forms of surface modelling now becoming available.

19.3 Dot density patterns

Of all the various methods of display, dot-density patterns have been the most widely used within the School of Archaeological Sciences. Their advantages are that they can be produced on almost any type of monitor and are entirely effective in monochrome, that a hard copy can be produced quite readily, that they do provide a true plan of the site, and that they are capable of bringing out almost every significant detail of the data, although perhaps not all at the same time.

The first dot-density program available in the school was written by Roger Walker (Walker 1980); it runs on a Hewlett-Packard HP1000 computer, using a Tektronix 4010 terminal for the display and a Tektronix 4631 printer for the hard copy. The density is created by plotting a random pattern of the appropriate number of dots over the grid cell, allowing some overlap into neighbouring cells. A smoothly varying density pattern is obtained in this way, but it is difficult to obtain very high densities, since the dots tend to overlie each other. Many users try to compensate for the lack of high density by working at very high contrast, often resulting in the loss of the intermediate levels. Nevertheless, the Walker program has provided sterling service for the school and continues to be a source of interest.

Later a simplified version of the Walker program was produced by Kelly (Kelly *et al.* 1984) for use on the Epson HX-20 portable computer, which continues to be the school's principal means of storage for newly logged data in the field. Although the Epson display is very slow, it provides field workers with a means of assessing their data as soon as they are logged. In its original form the program filled a 6×6 pixel array with a number of dots linearly related to the reading; the built-in printer gives a hard copy at a scale of 1:500. A variant of the program has been produced by A.R. Walker for use with his Geoscan instruments (Research 1986). The little Epson program has proved to have a usage far beyond what was envisaged for it when it was first written.

More recently the authors have produced another dot-density routine specifically for an Atari ST computer with monochrome monitor but, since the program is written mainly in standard FORTRAN 77, it should be readily adaptable to run on other machines. To produce a full screen image takes between 30 and 60 seconds, depending on the number of dots required, and a hard-copy of any image may be dumped to the printer at the discretion of the user. The scale of the printed copy may be selected by the user, the number of available pixels in each grid cell being adjusted to match the scale as accurately as possible. A random selection of the available pixels is set to give the final dot density a linear relationship with the original reading. A simple example of the printer output from this routine is shown in Fig. 19.2.

The main purpose of the routine was to assist the user in making a preliminary analysis of the data, and in deciding on an appropriate range of values for a contour plot, as discussed in section 19.4. Users have found it to be useful in its own right, especially in connection with magnetometer surveys. The linear proportionality of
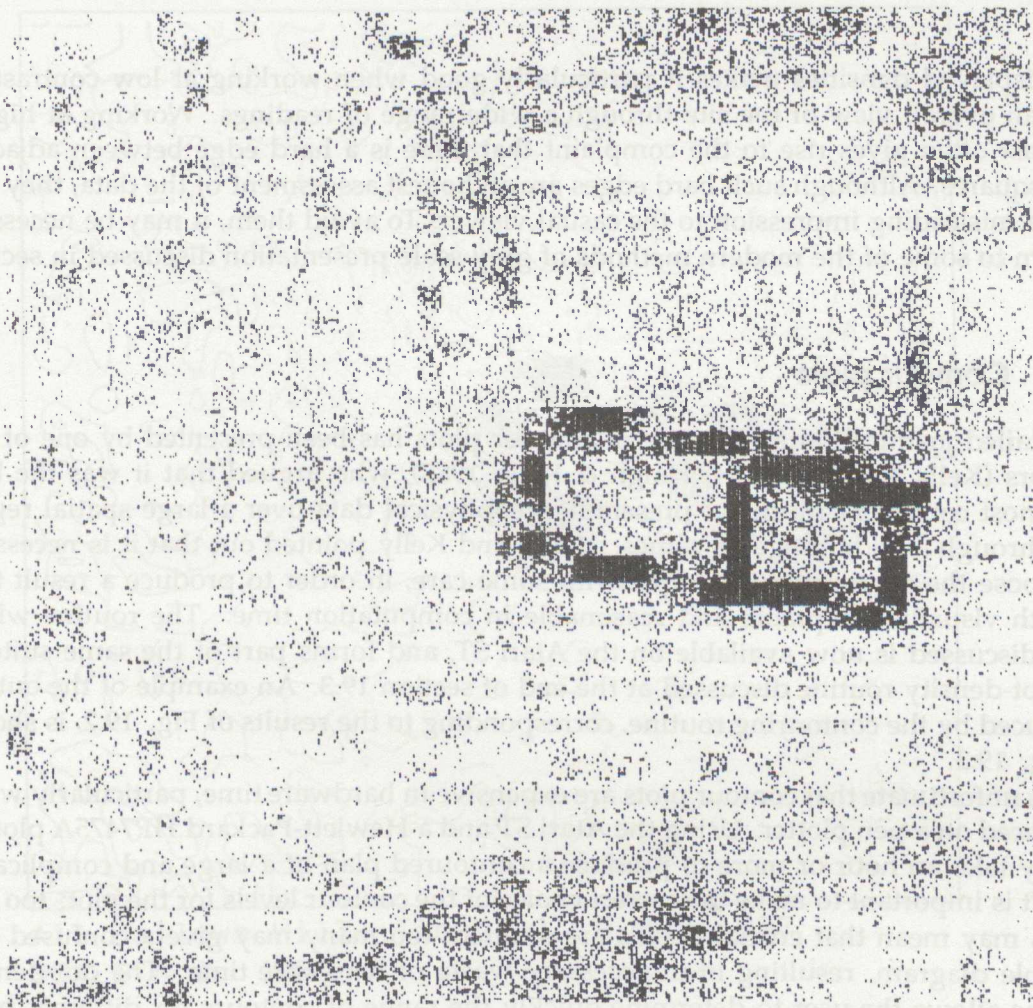
All Hallows Hill, Tickhill, 9 May 1987
SCALE = 1: 300

(1, 1)   (1, 2)

(2, 1)   (2, 2)

20 22 23 25 26 28 30 31 33 34 36

Figure 19.2: The results of a resistance survey displayed as a dot-density pattern.

the displayed densities makes it particularly good when working at low contrast, to give an overall view of the site through a wide range of readings. Working at higher contrast often gives rise to the complaint that there is a hard edge between adjacent grid squares. Although such hard edges are an honest assessment of the data, they can give a misleading impression to the casual viewer. To avoid them, it may be necessary to turn to some of the modern methods of grey-scale presentation discussed in section 19.5.
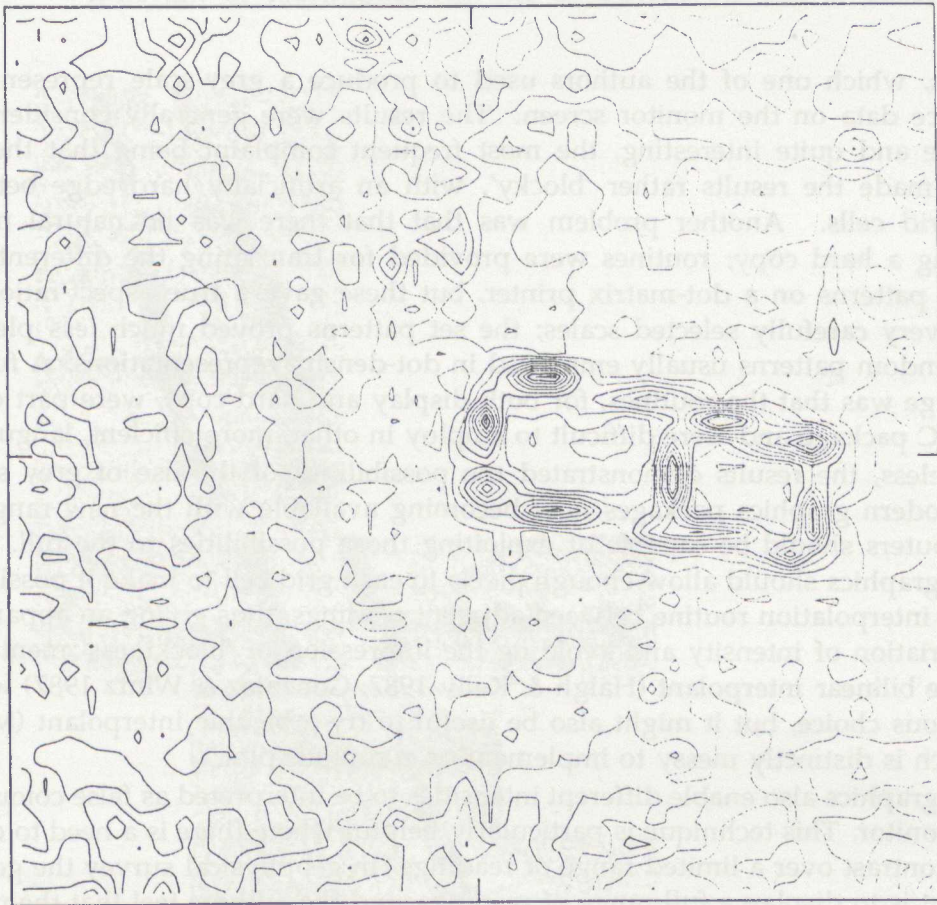
19.4 Contour plots

A detailed justification for the use of contour plots has been presented by one of the authors (Kelly & Haigh 1984, Haigh & Kelly 1987), who argued that it was the best and most consistent means of presenting geophysical data over a large spatial region and through a wide range of values. Haigh and Kelly pointed out that it is necessary to choose the contouring technique with some care, in order to produce a result that is both visually acceptable and reasonable in computation time. The routine which they discussed is now available on the Atari ST, and forms part of the same suite as the dot-density routine discussed at the end of section 19.3. An example of the output produced by the contouring routine, corresponding to the results of Fig. 19.2, is shown in Fig. 19.3.

It is unfortunate that contour plots are expensive in hardware time, particularly when produced on a pen plotter. Using the Atari ST and a Hewlett-Packard HP7475A plotter, it may take an hour or more to produce a contoured plan of a large and complicated site. It is important to make the correct choice of the contour levels for the plot: too few levels may mean that crucial details are omitted; too many may give a confused and illegible diagram, resulting in unnecessary waste of hardware time. The dot-density routine allows the user to determine quickly the range of contours for different parts of the site, and the contour interval to provide the correct contrast; thus a contour plot need not be undertaken until the user is virtually certain that the results will be acceptable.

The suite of routines also contains a facility for transferring logged grids from the Epson HX-20 portable computer to the Atari ST. It is assumed that each grid has been recorded at metre intervals in an array of 20 × 20 readings, and that all the grids are at the same orientation and in the correct relative positions. The relative positions are fed into a special report file as the successive grids are transferred to the Atari, so that an image of the entire site is gradually built up. It is possible to transfer a set of about seventy-five grids (30000 readings), to make a preliminary investigation using the dot-density method, and to produce a final report in the form of a contour diagram, all within a single working day. Such a data set represents about one week's fieldwork by a team working at the rate normally expected at the University of Bradford.

19.5 Grey scales and false colour plots

Several years ago the School of Archaeological Sciences obtained a Research Machines RML 380Z computer. Although this is essentially a conventional Z80-based machine of very limited capability, it possesses a graphics board which is quite advanced by the standard of its day. Among its display modes is one of 160 × 96 pixels in sixteen

All Hallows Hill, Tickhill, 9 May 1987
SCALE = 1:   250
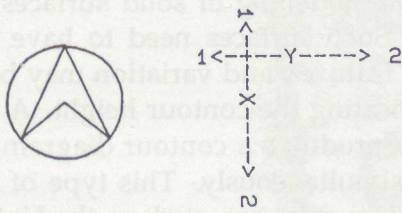
Contour	Level
11	45.0
10	42.5
	40.0
	37.5
5	35.0
	32.5
	30.0
	27.5
	25.0
	22.5
1	20.0

Figure 19.3: The data of Fig. 19.2 shown in a contour plot

grey levels, which one of the authors used to produce a grey-scale representation of resistance data on the monitor screen. The results were generally considered to be versatile and quite interesting, the most frequent complaint being that the low resolution made the results rather 'blocky', with an artificially hard edge between adjacent grid cells. Another problem was that that there was no natural means of obtaining a hard copy; routines were provided for translating the different grey levels into patterns on a dot-matrix printer, but these gave a true aspect-ratio only at certain very carefully selected scales; the set patterns proved much less pleasing than the random patterns usually employed in dot-density representations. A further disadvantage was that the routines, for both display and hard-copy, were part of the RML BASIC package and were difficult to employ in other, more efficient, languages.

Nevertheless, the results demonstrated the possibilities of the use of grey scales, and the modern graphics packages now becoming available with the new ranges of microcomputers should be capable of exploiting those possibilities to the full. High resolution graphics should allow enough pixels to each grid cell to make it possible to employ an interpolation routine between adjacent readings, thus giving an apparently smooth variation of intensity and avoiding the impression of 'blockiness' mentioned earlier. The bilinear interpolant (Haigh & Kelly 1987, Gonzalez & Wintz 1987) would be an obvious choice, but it might also be useful to try a bicubic interpolant (Mclain 1974), which is distinctly messy to implement on a contour plot.

Modern graphics also enable different intensities to be interpreted as false colours on a colour monitor. This technique is particularly helpful where there is a need to create a distinct contrast over a limited range of readings. In geophysical survey the general requirement is to display a full range of readings, and the authors feel that the use of false colours is more often confusing than helpful, except perhaps in picking out the extreme high readings and the extreme low readings. One use of false colour which may commend itself for the future, is in the modelling of solid surfaces, as opposed to the wire-frame models of Section 19.2. Such surfaces need to have some colour variation in order to show up their detailed features, and variation may be introduced by painting a surface with false colours indicating the contour height. A projection of the surface on to the xy-plane automatically produces a contour diagram, thus giving the viewer two interpretations of the data simultaneously. This type of modelling is already becoming available in modern graphics software, such as the Uniras package.

There are some occasions when the discreet use of colour would clearly be helpful. In magnetometer survey, for instance, there is an obvious difference in interpretation between the positive features and the negative feature; this is illustrated in Fig. 19.4 where the positive readings are shown in black, and the negative in white, against a mid-grey background. These effects would be seen more clearly if the positive readings were shown in shades of (say) red and the negative readings in shades of blue, with zero values remaining white. Sensible use of colour would also be helpful in combining and contrasting spatial results from different techniques of observation, as is discussed in Section 19.7.

The technology of small printers is advancing in parallel with the development of high-quality monitors, so that it is now possible to obtain hard copies of both coloured and grey-shaded images at reasonable cost. One can therefore look forward to the rapid application of modern graphics to geophysical data; it is probable that dot-density patterns and wire-frame models will be largely displaced, as also may pen-drawn

Figure 19.4: The results of a magnetometer survey shown as a dot-density diagram. Positive readings (dark) and negative readings (white) are clearly distinguished, and represent ditches and probable baulks respectively.

contour plots.

19.6 Image processing operations on geophysical data

Particularly when it is displayed by means of dot densities or grey scales, it is natural to think of the pattern of observations produced by a geophysical survey as a form of image. The next step is then to apply standard techniques from image processing, so that the image may be enhanced by conversion into a form that seems more acceptable, or more illuminating, to the beholder. Consequently programs for the analysis of geophysical data tend to incorporate some image processing techniques.

Among the most familiar of these techniques is the facility to replace each reading by a linear combination of the 3×3 (or larger) array of neighbouring readings. Such operations are often called filtering procedures and, specifically, a simple average over the neighbouring array may be referred to as a 'low-pass' filter, while subtracting a proportion of the neighbours may be referred to as a 'high-pass' or 'Laplacian' filter. Strictly speaking, these operators should not be referred to as filters, since filtering takes place in the frequency domain and not in the spatial domain, but as masking operations or convolvers. It is true that every frequency filter is equivalent to a spatial convolution, but the convolutions corresponding to good smooth filters such as Butterworth filters (Gonzalez & Wintz 1987) are much more complicated than 3×3 masks.

The justification for the use of 'low-pass filters' is an attempt to smooth the data, particularly by the removal of noise. In this connection, it should be noted that noise reduction can often be achieved much more satisfactorily by a median mask than by simple or weighted averaging (Rosenfeld & Kak 1982, Gonzalez & Wintz 1987). Moreover, attention should be given to what is meant by noise, since electronic noise is rarely a major problem in either resistance or magnetometer survey. It is more likely that the apparent noise is genuinely part of the signal from the ground, and should be smoothed out only after careful consideration. There is evidence, for instance, that in resistance survey some objects may give rise to a sharply peaked signal whose spatial size is considerably smaller than their own. When observed on the usual grid of readings at one-metre intervals, the sharp peaks may be seen as a series of disconnected spots, as is shown in Figs. 19.2 and 19.3. Any attempt to smooth out the spots might result in loss of the very evidence that the survey had set out to discover.

The break up of a narrow spatial feature into a series of spots is a well-known phenomenon in image processing, where it is called 'aliasing'. The effects of aliasing cannot be eliminated by any of the standard methods of image enhancement, but only by taking readings at smaller intervals in an attempt to increase the resolution. On the other hand, to change from a one-metre interval to a half-metre interval increases the required effort by a factor of four, making it necessary to balance the increase in effort against the gain in information, especially when one may be approaching the effective limit in resolution of the detector. The bicubic interpolation, mentioned in Section 19.5, could enhance the appearance of aliased results, but this treatment would be purely cosmetic and would not solve the underlying problem.

The aim of the Laplacian mask is to sharpen edges, and is thus almost exactly opposite to that of an averaging mask, which tends to soften edges. To achieve reliable edge enhancement requires something considerably more sophisticated than a simple Laplacian mask (Rosenfeld & Kak 1982). Generally speaking, if there are real edges in

the data, at no matter how low a contrast, then they can be revealed by careful display without need for masks or filters.

Having experimented with filters, usually with the aim of removing a specific effect (often of geological origin) from a particular set of data (Kelly 1986), the authors do not favour the use of filters on geophysical data, except in special circumstances. It must not be assumed that a set of geophysical data is exactly equivalent to an image. While a digitised image almost invariably consists of a complete rectangular array of pixels, a geophysical dataset may be of irregular shape and contain large blocks of missing values in its interior, making it difficult to apply some enhancement techniques. Furthermore, the physical processes which give rise to the geophysical signal are usually much more complicated than those involved in image formation.

Following these arguments, the authors have at present included in their data analysis package only one smoothing technique, whose aim is to remove isolated noise spikes without a general smoothing (Rosenfeld & Kak 1982), and which allows a reading lying well outside the range of its eight neighbours to be replaced by a new value interpolated from the neighbours. This technique is quite useful for filling in odd values which cannot be read because of tree stumps or large stones, and has been found on occasion greatly to enhance the appearance of a contour plot.

Besides masking or filtering, another important group of techniques from image processing is provided by histogram equalisation and histogram specification. These determine how the available intensities are to be matched to the range of readings; with equalisation a uniform spread of intensity is achieved automatically, whereas specification gives the user the ability to match the distribution of intensity to personal preference. At least one program has incorporated these features (R. 1987), and the authors have been impressed by some of the improvements which it is capable of achieving. Histogram equalisation seems to be the more desirable feature, since it gives an optimal enhancement without involving the user in time-consuming decision making. On the other hand, the data structure currently used in the authors' program makes it somewhat difficult to incorporate these features, which are regarded as possible improvements for the future.

The techniques described so far in this section constitute the basic methods of image enhancement. Beyond them are more complex methods, usually grouped under the heading of image restoration, including Fourier filtering and the modern optimisation techniques such as the entropy method. The fact that they are very expensive in computer time may make it inappropriate to apply them interactively on the present range of small computers, but with the continuing improvement in processor power they could become available in a few years' time. Difficulties will continue to arise from the irregular outline of many geophysical surveys and from the complex nature of the recorded signal, but it is surely better to employ methods specifically chosen to match the nature of the problem than to endorse the blanket application of simple masking techniques.

19.7   Combining results from different sources

Preliminary information about a site, in advance of excavation, may come from several different sources—from different forms of geophysics, such as resistance or magnetometry, from micro-contour surveys, from surface collection, and from aerial photography.

Each source provides a characteristic type of information and is capable of producing its own site plan; in order to gain maximum advantage from the overall set of data, it is necessary to be able to compare and contrast the various plans. One obvious way to provide the basis for comparison is through the sensible use of colour, using a different colour plane for each source of information and producing particularly intense colours where different sources corroborate each other. Clearly the number of sources that can be presented simultaneously must be restricted by the number of independent colours available.

The problem of bringing spatial information from different sources together is not merely one of display, but also of database. Archives should be organised so that it is possible to discover what information from each source is available for the relevant area, and then to bring the spatial distributions into exact coincidence. Up to the present few workers have thought in terms of creating records with the necessary global accuracy, and there has been little attempt to produce national archives. The juxtaposition of evidence from aerial photography and from geophysics is already becoming recognised as one of the most important advances in non-destructive archaeology. There can be little doubt that techniques for the combination of different types of spatial information will develop strongly over the next few years, and exciting prospects are created by the ability of modern graphics to 'paint' different distributions on to an appropriate background.

19.8 Summary and conclusions

The authors have found their existing program to be entirely successful in its aim of providing a speedy and reliable service for the analysis of geophysical data. The screen display of dot densities provides rapid access both to a summarised view of an entire site and to details of any portion of the site. A permanent record of the results is conveniently obtained by a standard printer dump of the screen; particularly in the case of magnetometer survey, the printer dump is often regarded as an adequate presentation at all stages up to report level. Otherwise the dot densities may be used to ascertain the contour levels necessary to bring out all the details revealed by the survey. The contours can then be drawn on a pen plotter, a process which can be somewhat lengthy and complicated, but which is capable of presenting the complete range of detail in a single plan.

In the authors' opinion, extreme caution should be exercised before applying image processing techniques to geophysical data. The inconsidered application of standard masks may disguise the very evidence that the survey was intended to reveal and lead to entirely fictitious conclusions. Consequently the authors have introduced only very limited applications of such methods into their program, and are likely to consider only very specific techniques for introduction in the future.

The advent of more powerful computers should lead to the introduction of improved graphics techniques in the near future. In particular the authors look to grey-scale distributions to provide an improved alternative to the ubiquitous dot-density patterns. Coloured graphics are likely to be helpful in emphasising particular aspects of the results, and also in providing a basis for comparison between data from different sources. It should always be remembered that the criterion for judging the effectiveness of a graphical presentation is not its aesthetic quality, but its success in allowing the

user to make an unbiased and complete assessment of the data. It seems that the criterion has been, or is about to be, satisfied and that the problems of archaeological geophysics now rest where they should be, namely in obtaining the information from the field, not in its subsequent analysis.

The authors are grateful to Miss Evelyn Pugh, who has been responsible for much of the practical testing of the ideas set out in this paper, and to Dr Bob Yarwood of the West Yorkshire Archaeological Service, who kindly provided a demonstration of his programs running on the Atari ST computer.

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