Magnetic Methods of Archaeological Prospecting-Advances in Instrumentation and Evaluation Techniques

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Magnetic methods of archaeological prospecting—advances in instrumentation and evaluation techniques

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Rapid survey of many minor archaeological sites gives a more balanced picture of the past in a given region. The development of accurate portable magnetometers now allows mapping of such buried sites in many types of soils. New differential instruments are more convenient, eliminating most external disturbances. The major remaining problem is the separation of weak archaeological magnetic 'signals' from 'noise' due to minor geological irregularities. Digital filtering, nonlinear processing and a system of data display which makes use of the eye's ability to see faint shapes in confused backgrounds have been developed for use with a large computer. Optimum filter techniques can be worked out from computed theoretical model studies of signals and noise.

Introduction

When we are concerned with determining the ultimate effectiveness of a communications link, we study the properties of the signals and noise encountered. It is convenient to consider the problems of ultimate sensitivity in archaeological magnetic prospecting along analogous lines. The magnetic anomalies produced by features of archaeological interest will henceforth be called signals, and all sources of disturbance regardless of origin will be called noise. Of course, our signals are not time variant since the buried features are not moving about, and for the most part neither is our noise, so that the analogy with the communications case is not perfect.

The strength of the archaeological signal is a function of buried feature geometry, depth, and magnetic contrast relative to the surrounding soil. Noise is of various origins. It can be divided into two main classes depending on whether it is correlated or not. Uncorrelated noise is completely independent from measurement to measurement over an area. Correlated noise is not. Noise of the uncorrelated type includes disturbance of the measurement by passing vehicles, power line and earth current transients, very short-term variations in the Earth's magnetic field, magnetometer errors coming from amplifier noise or counting and errors due to variations in the exact position of the sonde from one measurement to the next relative to an ideal measurement grid. Errors in the orientation of the sonde relative to the Earth's field, if these exist, are sometimes uncorrelated, sometimes not, depending on survey technique. Correlated errors are mainly due to non-archaeological irregularities in the superficial geology of the measured area and, if not otherwise compensated, long-term changes in the Earth's magnetic field and in the magnetometer itself.

First, let us consider some properties of the signal. Archaeological features are often of regular geometric shape. In many cases they can be accurately described in terms of combinations of linear, curved and isolated elements. This allows computation of a theoretical anomaly with considerable precision (Scollar 1969). For example, the anomaly produced by a 5 m wide east–west ditch of triangular cross-section, 3 m deep, buried 1 m under the surface of measurement at a field value typical of northern Europe is 40 γ† when the soil susceptibility contrast is 10^{-3} e.m.u./cm^3.

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† $1\gamma = 10^{-5}\,\mathrm{Oe} = 10^{-2}/4\pi\ \mathrm{A\,m^{-1}} \approx 7.96\times10^{-4}\ \mathrm{A\,m^{-1}}$.

As Le Borgne (1955, 1960) has shown, if a susceptibility contrast exists at all between the upper and lower soil layers, it may be expected to lie roughly in the range of 10^{-5} to 10^{-3} e.m.u./cm^3. Since the strength of the magnetic anomaly due to the archaeological feature is proportional to this contrast, assuming that the filling of the feature contains a large amount of surface material, anomalies from typical ditches of the size mentioned above may be expected to run between 0.4 and 40 γ, depending on soil. With smaller ditches or greater depth of burial, the anomalies will be smaller. With features closer to the surface or of larger size, greater anomalies may be anticipated. For remanently magnetized features such as kilns, anomalies may be higher than that suggested by the Le Borgne contrast. Isolated features like pits will generally be weaker than long linear features of similar cross-section. Hence, a total anomaly range from 0.1 to 100 γ may be expected for almost all cases.

To obtain adequate resolution of fine detail, it is tempting to think that instrument sensitivity must be as high as possible, i.e. better than 0.1 γ for the worst soil case. In fact, it may not be possible in practice to utilize the sensitivity available in some instruments unless sophisticated evaluation routines are also followed. With their help, even measurements made at low sensitivity can be made to yield useful results for favourable feature geometries.

Instruments

The single device which has had more impact than any other is the magnetometer using free proton precession. The phenomenon was first observed by Packard & Varian (1954). It was developed simultaneously by them and by Bradshaw (1956), Waters & Phillips (1956), and Waters & Francis (1958), into a useful magnetometer, and this design, with modifications was employed, first by Gray in 1956, then by Aitken in 1958. Belshé apparently was the first to use a proton magnetometer on an archaeological problem, when he employed a device similar to Gray's to monitor the test firing of a reconstructed Roman kiln at Wattisfield in Suffolk in the summer of 1957 (Belshé 1957). On his recommendation the prototype of the Elsec magnetometer was built at Oxford and was used for the first observations of buried kilns and ditches at Water Newton by Aitken in early 1958 (Aitken, Webster & Rees 1958).

The Waters & Francis circuit uses a period counting scheme for precise measurement of the low-frequency precession signal. The absolute value of the Earth's field can be inferred from the reading to about 1 γ in northern latitudes. Somewhat greater accuracy is possible at the expense of measurement time by extending the counting interval. This is practical only during extremely calm magnetic periods. Correction for diurnal variations in the Earth's field which amount to more than 20 γ on quiet days is essential if the ultimate accuracy of the instrument is to be utilized. In the presence of magnetic storms, severe ground current transients and other external disturbances, the order of accuracy may be very much reduced.

An advance on the scheme of Waters & Francis was proposed by the author who designed the first digital differential proton magnetometer (Scollar 1963). The 1960 prototype has gone through many versions. Two sondes are used and the difference in magnetic field at two points along with the sign of the difference is indicated directly. The latest version incorporates astatically wound noise cancelling sondes, phase locked loop multiplication of the proton frequency as suggested by Serson (1962), digital subtraction with sign indication, with difference shown directly in gammas or tenths of a gamma. Sensitivity to all sources of external disturbance is well below the least significant figure. No correction for diurnal change is required.

When carefully used, magnetometers of the Waters & Francis or Serson types are capable of giving results resulting in residual uncorrelated errors of a gamma or so. The author's differential version of Serson's design affords about an order of magnitude improvement on this. Further work may allow some increase in sensitivity, but it seems doubtful that much less than 0.1 γ error will be achieved using free precession in a portable instrument.

Optical pumping, applied to magnetic measurement was announced by Dehmelt (1957) and developed for practical magnetic measurement by Bender (1960). A number of years passed before an instrument designed for archaeological purposes appeared. The Varian company produced a differential portable version of their caesium vapour instrument for the University of Pennsylvania Museum (Ralph, Morrison & O'Brien 1968) with a sensitivity of about 0.5 γ in difference mode, depending on latitude. The orientation dependence of single cell optically pumped magnetometers precludes attainment of much greater sensitivity than this under field conditions unless both sondes are rigidly mounted on the same staff and carefully balanced for errors magnetically. Absolute accuracy is probably an order of magnitude lower than the sensitivity figures indicate. The Varian design does not incorporate digital subtraction and no provision is made for sign indication. The instrument zero is field dependent and hence complete cancellation of external disturbance is not carried out. In use, permanent magnets have been employed to back off the field at one sensor (E. K. Ralph, private communication). This practice may introduce some correlated error due to dependence of the field of the back-off magnet on ambient temperature.

Carefully applied, optical pumping could be capable of very high sensitivity with moderate accuracy. In the scalar helium gradiometer, developed by Slocum (1969) at Texas Instruments, a recording taken over 25 s with 0.3 s averaging time shows fluctuations of less than 0.01 γ difference. Freedom from orientation effects is obtained by the use of six absorption cells in each of the two sondes. The very high Larmor frequency produced by optically pumped helium makes errors due to movement of the sonde during measurement much less than that occurring in free precession devices. Absence of heating arrangements required by alkali vapour devices is also valuable. Though these instruments have not as yet become available for archaeological prospecting, it would seem that they promise an order of magnitude improvement for the future. The same may be said of the electron spin resonance pumped magnetometer of Salvi (1969) based on the Overhauser–Abragahm effect which achieves results similar to Slocum's device. However, its sensitivity to movement is the same as free precession instruments and this will probably limit attainable field sensitivity.

For greatest immunity to external noise and strong local gradients, the long-based flux gate gradiometer of Alldred and Aitken (Alldred 1964) should be mentioned. Its sensitivity is somewhat less than that of the free precession devices, but it can be used where work with almost any other instrument is hopelessly upset by external noise.

Finally, one must note the 'Maxbleep' of Aitken & Tite (1962). This highly simplified device, giving a qualitative indication of gradient only can, in the hands of a skilled operator, yield very useful results with sensitivity down to about 2 γ. Its use is restricted to small scale surveys where little or no numerical evaluation is needed.

Noise

It is evident that the sensitivity of the available instruments is capable of dealing with many of the anomalies produced by typical archaeological features in all but the most weakly magnetic soils. However, this sensitivity does not remove the problem of correlated soil noise. The uncorrelated noise sources will, with time, be reduced by progress in instrument design. Correlated soil noise due to random irregularities in soil structure cannot be removed. The degree of correlation depends on the size of the disturbances. A typical plot of such noise can be seen in figure 1. Measurements were taken over nearly a hectare without evident archaeological features in a comparatively uniform loessic soil lying thinly on river terrace gravels. The main source of the disturbance appears to be irregularity in the gravel deposits, as visible in an air photo of the same area.

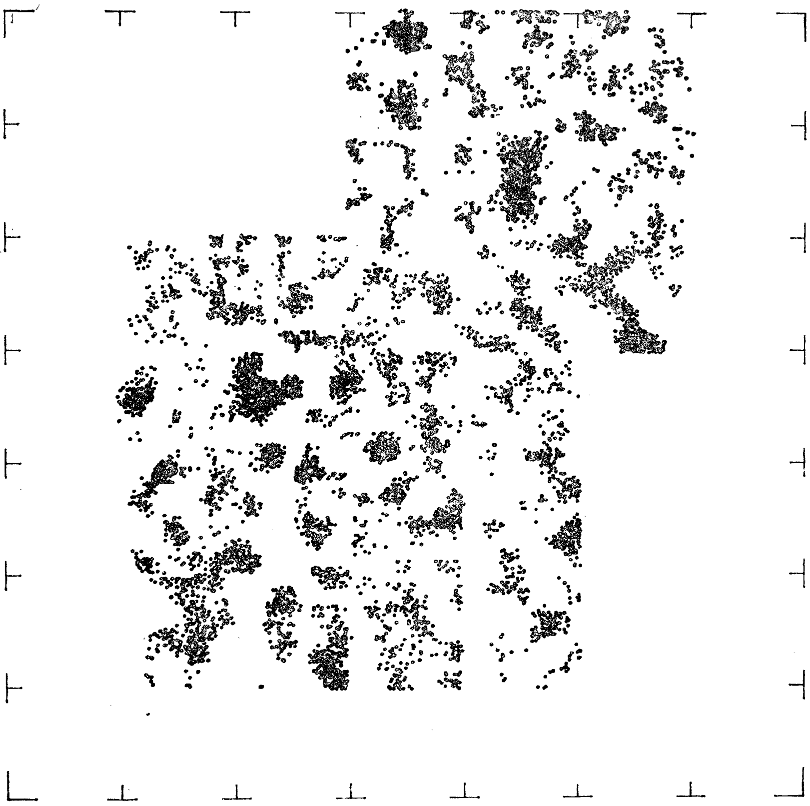

Figure 1. Magnetic map (dot density) of soil noise, loess on Upper Rhine terrace gravels.

To some extent, soil noise depends on the Le Borgne contrast as well as the subsurface structure. Highly uniform sedimentary soils with low Le Borgne contrasts are quieter than those developed on hard rock close to the surface with high Le Borgne contrasts (Scollar 1965). Small irregularities in highly magnetic soils (pebbles in volcanic deposits) increase the noise level considerably but with suitable measurement spacing will be largely uncorrelated (Cook & Carts 1962). Experience indicates that noise amplitudes are roughly of the same order of magnitude as those produced by the archaeological anomalies or, in soils developed on hard rocks, slightly greater. When this is true it is very difficult to see archaeological features in raw data or contour plans.

It is useful to examine the properties of soil noise statistically, that is, in terms of the relative amounts of anomalies of varying lateral extent present in the data. The graph of these relative amounts is a distribution. Since the measurements are made over an area, the distribution contains lengths running in two directions at right angles to each other. If the amplitude or relative amount of a given pair of lengths is plotted at right angles to these, a three dimensional figure results. By analogy with optics we may think of such distributions as being spectra of spatial wave-lengths with band limits set by the sampling (measurement) interval at the short wavelengths, and by the maximum size of the measured area at long wavelengths. The spectra are obtained from the data by taking its two dimensional Fourier transform, an operation of some complexity which yields the desired information.

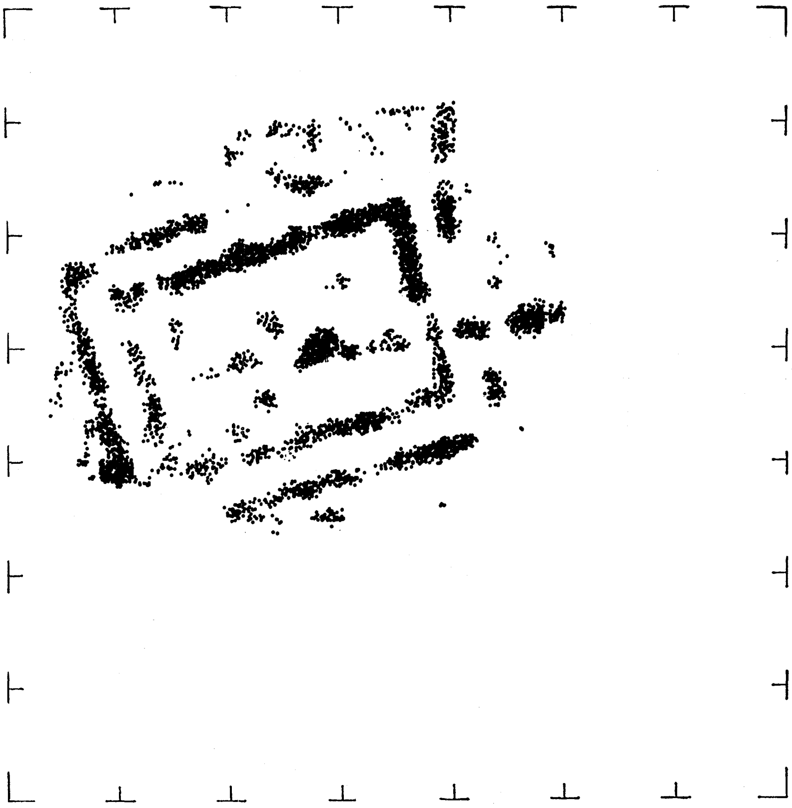

FIGURE 2. Magnetic map (dot density) of Roman site at Froitzheim, Kreis Düren.

Real data yields a Fourier transform containing complex numbers, half of which are the complex conjugates of the other. For display, only the magnitude of the entire transform is plotted. This does not contain all the information available, but it is much more readily visualizable. For the large data arrays with which we have to deal, it has become feasable to carry out this calculation quite quickly since the Cooley–Tukey fast Fourier transform algorithm became available in late 1965 (Cooley & Tukey 1965). For data from archaeological sites, a modification of this algorithm (Black & Scollar 1969) has been used to compute the figures which follow.

For magnetic signals and noise from a very low noise archaeological site, figure 2, the Fourier transform looks rather like a rumpled carpet, figure 3. In this figure the convention has been adopted whereby the relative amounts of long wavelengths are shown by the peaks in the centre of the plane, the short wavelengths out at the edges. The edge of the plane is termed the Nyquist limit. If we assume that irregularities in soil give rise to large numbers of randomly distributed magnetic dipoles, we can compute a number of distributions to see which corresponds most closely to those encountered in real data. The magnetic dipoles are assumed to be assigned random numbers as coordinates in the horizontal plane with equal likelihood. We may then choose a number of possible ways in which the depths of the dipoles are specified. An equal likelihood depth characteristic produces the spectrum shown in figure 4. It contains components more or less equal in amplitude right out to the Nyquist limit. A distribution of depths which produces a spectrum more like that encountered in practice, is one following a normal probability curve with its peak at several depth units. The likelihood of a dipole occurring is less near the surface or at great depth. The spectrum for this distribution is shown in figure 5.

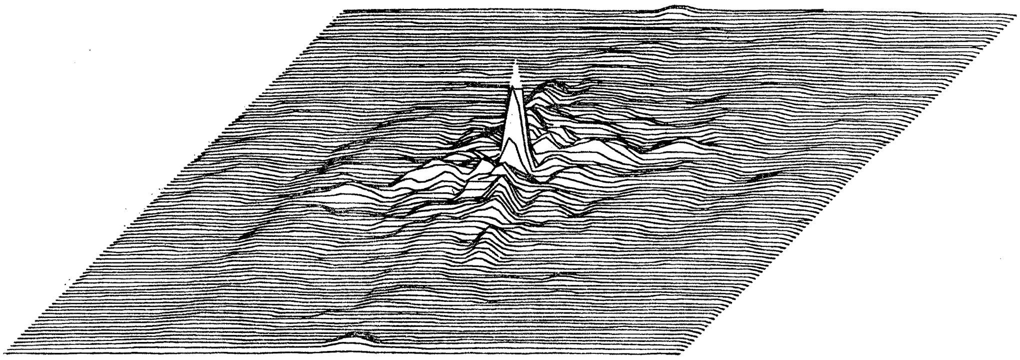

FIGURE 3. Modulus of the Fourier transform of the data in figure 2.

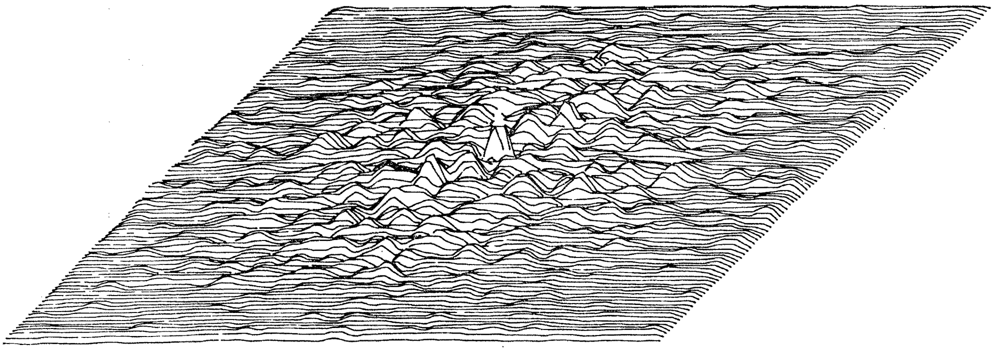

FIGURE 4. Spectrum of simulated soil noise, equal probability vertical dipole distribution.

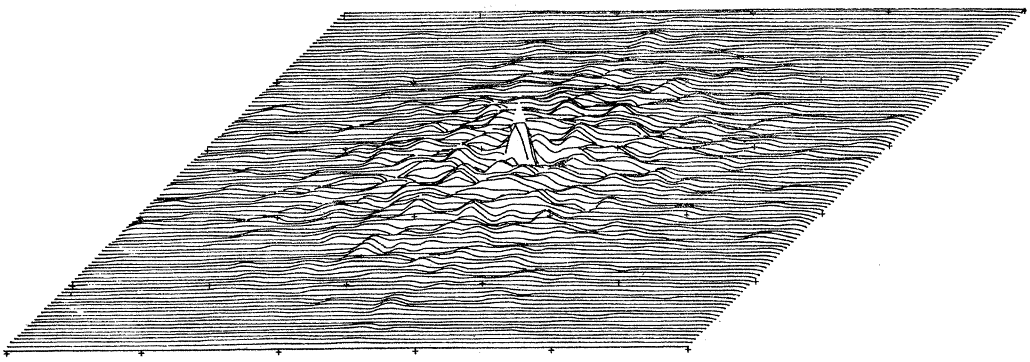

FIGURE 5. Spectrum of simulated soil noise, Gaussian probability vertical dipole distribution.

It can be seen that the shorter wavelengths are not as strong as in the linear case of figure 4. The spectrum of the noise from the real measurements of figure 1 looks very much like figure 5.

Uncorrelated noise, whatever its source, produces an amplitude spectrum which is uniform over the entire Fourier plane. The spectra of uncorrelated and correlated noise can be added linearly to obtain the combined spectrum of soil and instrument noise. By analogy with optics, let us call the middle of the Fourier plane 'red', the edges 'blue'. A uniform distribution such as that due to uncorrelated noise is then 'white', since all spectral components are equally present. Hence the spectrum of correlated noise with normal probability vertical dipole distribution which is somewhat raised toward the red end, when added to instrument white noise produces a pink combination. It is this pink noise which our evaluation technique must ultimately treat.

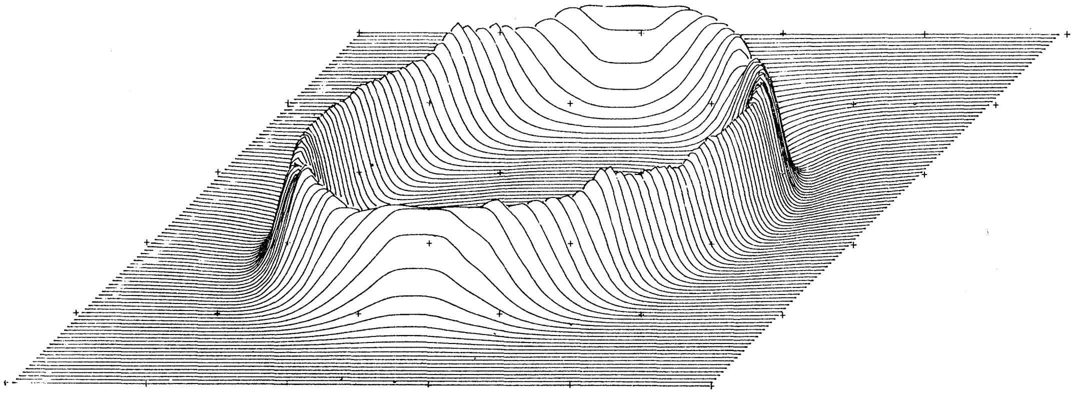

FIGURE 6. Pseudo-perspective plot, magnetic field due to circular ditch of triangular cross-section.

SIGNALS AND FILTERING

What do the spectra of pure signals look like? It is intuitively obvious that monuments which contain long linear features are productive of highly correlated magnetic readings from one point to the next in certain directions. A circular ditch of triangular cross-section buried at some depth produces a magnetic anomaly whose three-dimensional picture looks like figure 6. The magnitude of the Fourier transform of this signal looks like figure 7. It can be readily seen that the spectrum contains only elements in the centre of the Fourier plane and hence is pronouncedly red. On the other hand, isolated features such as pits, kilns, etc., produce spectra which look more like those due to soil noise.

This observation leads to a technique by which one can enhance signals at the expense of noise, using the high degree of correlation (redness of the spectrum) characteristic of linear anomalies. To test this method, suppose we combine the signal from the circular ditch with noise made by 1000 random dipoles, setting the signal to noise ratio at 1:2. The result is figure 8. If we did not know that a signal was present, we probably would not suspect it in the pseudo-perspective computer display. But we now know that the spectra of signals and noise differ considerably if long features are present. So we take the Fourier transform of the *mixed* data, which gives us the spectrum of signal plus noise. Using an appropriate array of coefficients, we diminish the values of the mixed spectrum away from the centre of the Fourier plane. This array of coefficients is termed a 'filter'. A very good filter would be the normalized spectrum of the sought-after signal itself, but in practice we do not know this. A fairly good choice will be something like it, say a bell-shaped curve rotated about its axis and centred in the middle of the Fourier plane. After filtering, we take the inverse Fourier transform of the filtered spectrum and the result is data, modified, as shown in figure 9. We have recovered our circular anomaly in recognizable form with only a few additional wobbles. This technique is described in full mathematical detail in Black & Scollar (1969).

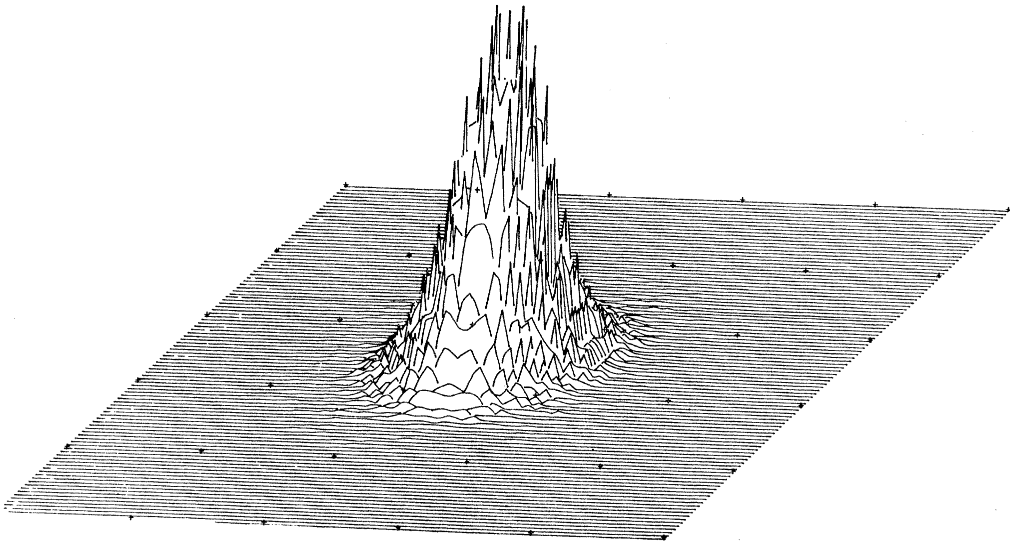

Figure 7. Spectrum of figure 6 data.

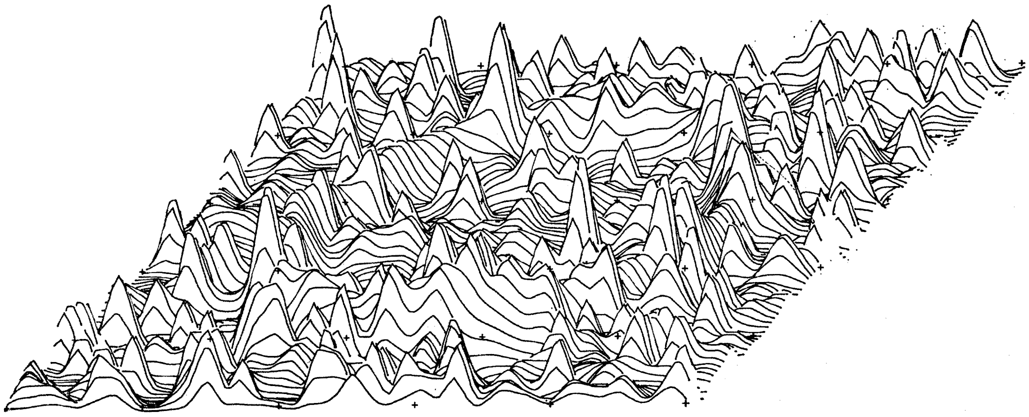

Figure 8. Mixture of data from figure 6 with noise, distribution as in figure 4, signal/noise ratio 1:2.

In the foregoing example, a circularly symmetric signal was chose for simplicity. In practice, our features are but rarely circular and nearly never centred at the origin of the measurement grid. A typical signal might be that due to a double-ditched Roman fort, the ditches triangular in cross-section, the fort square in shape with rounded corners and entrances on two sides. The Fourier transform of this signal looks like figure 10. It contains not only large amplitudes at the centre of the plane, it also has four lobes extending outward. If the noise were purely white, then the normalized spectrum of this sought-after feature would constitute the ideal filter. The filter must be rotated through a selection of angles until the lobes correspond with those present in the transform of the real data, this giving the best output from the inverse Fourier transform. Since in practice noise is not white but pink, the filter must be slightly altered to achieve optimum separation of signal and noise. This is done by subtracting a cone of values having sides tapered according to the wavelength envelope of the spectrum of real soil noise from the filter.

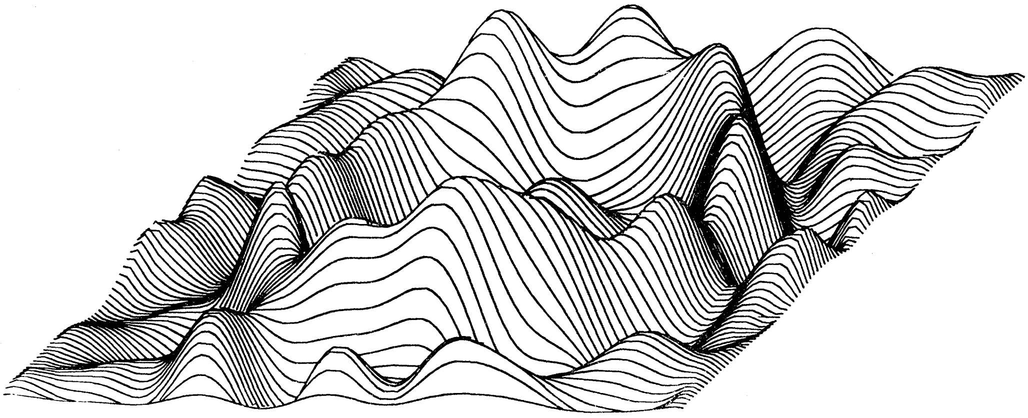

FIGURE 9. Data of figure 8 filtered in the Fourier transform plane, inverse transform.

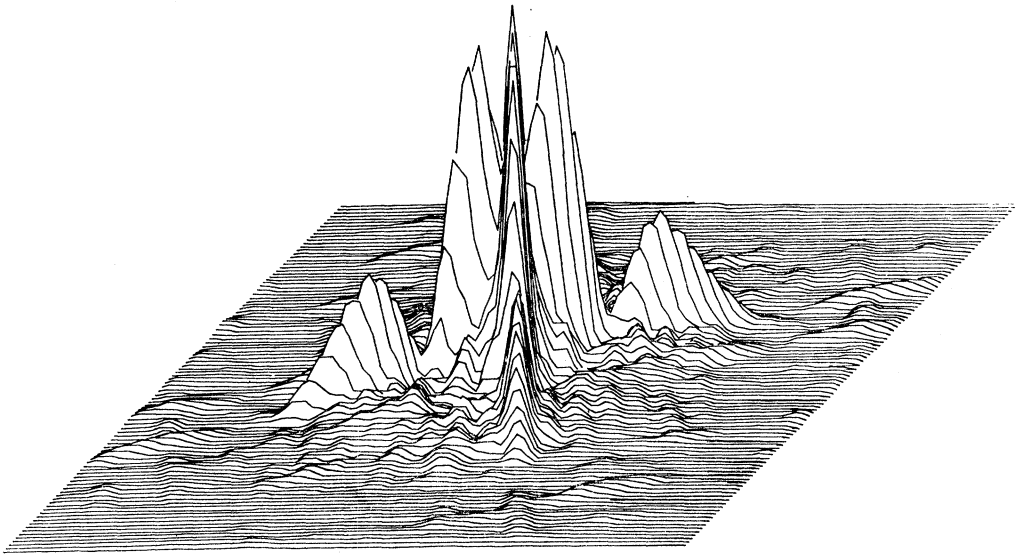

FIGURE 10. Spectrum of data from simulated Roman camp, double ditched, triangular cross-section, rounded corners, entryways.

All of the foregoing demands a lot of a computer, even a very large one. It may one day be better to do this job with coherent light, correlators and rapid rotation of the filters in the reference path. The eye might then be able to pick out the relevant shapes due to persistence of vision. Since we seldom know as much about signals as has been assumed here, many different filters will have to be tried and the best picture built up gradually. Doing the job optically would mean that the results could be seen at once and recorded on film. Improvements could be made progressively. With proper preparation of the filters, the archaeologist might even be able to do the job himself.

DATA DISPLAY

For subsequent optical processing, the raw data must be transformed into an image whose density is related to anomaly strength. This has been done for some time anyway when data are available in digital form. A computer drawing is obtained which was christened a dot density plot (Scollar & Krückeberg 1966). In special installations (Scollar 1968) the field record is obtained directly on punched paper tape with automatic recording of position and reading from a differential magnetometer. The dot plot is made by introducing small random displacements from integral position coordinate values at a fixed scale reduction of the field data.

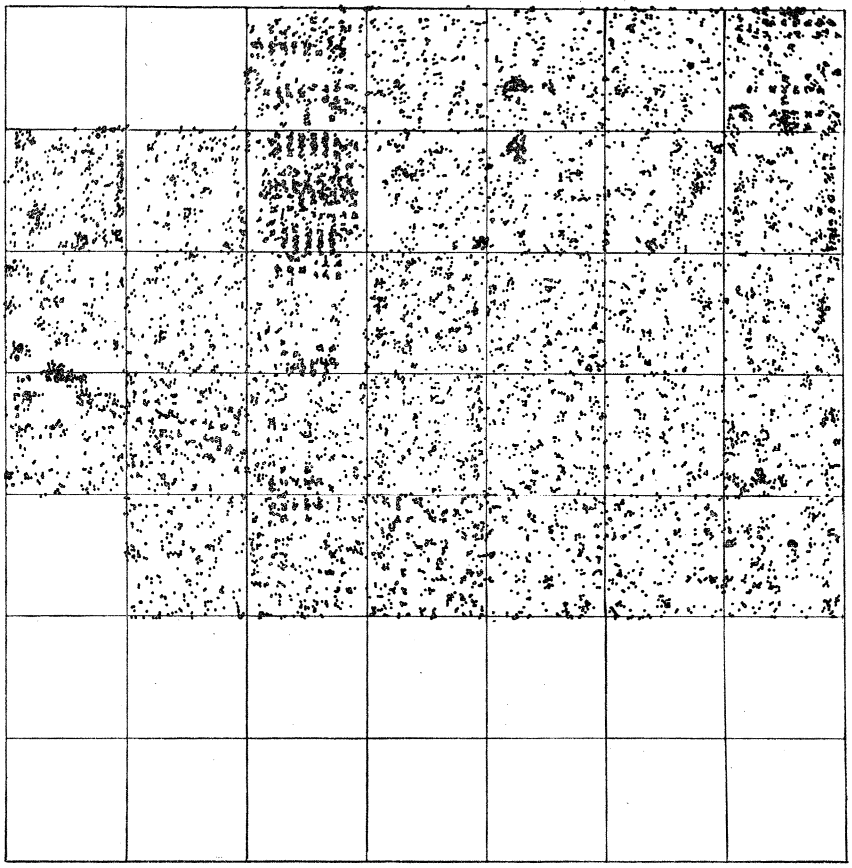

FIGURE 11. Dot density plot, prehistoric enclosure, no filtering, signal/noise ratio *ca.* 1:10.

The number of dots is related in a simple way to the raw data. A similar result can be obtained at the expense of much coarser quantizing using symbols of progressively increasing area. With some practice dot plots can readily be made by hand. Since the human eye is very sensitive to linear correlations in this type of data, features well below the level of instrument noise can be picked out even in unfiltered data, as seen in figure 11, where a rectangular enclosure can faintly be seen buried under the correlated and uncorrelated noise of the surroundings. Contour presentation, commonly chosen for geophysical survey, is very unsuited to data as noisy as this. Filtering will remove many of the random dots, allowing the eye to see correlations still better.

In practice, it is useful to use nonlinear techniques before and after filtering to prevent disturbances of large amplitude from overloading either the filters or the plotter. Wild values are also removed in this way. Using the combined techniques, a very considerable enhancement in the detectability of an archaeological feature is obtained, regardless of the type of instrument employed in making the survey. The dot density plot allows signals somewhat below the noise level to be seen readily. With transform filtering, and especially with optimum filtering using theoretical anomaly spectra as filters, an order or more of magnitude improvement is obtained. Even for isolated features whose magnetic contrast is less than that predicted by the Le Borgne effect, the filtering technique will afford some improvement gained through reduction of uncorrelated instrument noise. This is less spectacular than the results achieved with linear features, but it is useful none the less.

Given a suitably sensitive and accurate instrument and a monument of reasonable size measured carefully at close intervals, a useful result may now be achieved in almost any soil where a measurable Le Borgne contrast is present and where this material is incorporated in the features of archaeological interest. The magnetometer, a very sophisticated shovel indeed, should now be added to the archaeologist's tool kit for a great number of tasks, especially those for which the classical shovel is uneconomical.

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