1

INTRODUCTION

1.1 Fields

Although there are many different geophysical methods, small-scale surveys all tend to be rather alike and involve similar, and sometimes ambiguous, jargon. For example, the word *base* has three different common meanings, and *stacked* and *field* have two each.

Measurements in geophysical surveys are made *in the field* but, unfortunately, many are also *of* fields. Field theory is fundamental to gravity, magnetic and electromagnetic work, and even particle fluxes and seismic wavefronts can be described in terms of radiation fields. Sometimes ambiguity is unimportant, and sometimes both meanings are appropriate (and intended), but there are occasions when it is necessary to make clear distinctions. In particular, the term *field reading* is almost always used to identify readings made *in* the field, i.e. not at a base station.

The fields used in geophysical surveys may be natural ones (e.g. the Earth's magnetic or gravity fields) but may be created artificially, as when alternating currents are used to generate electromagnetic fields. This leads to the broad classification of geophysical methods into *passive* and *active* types, respectively.

Physical fields can be illustrated by lines of force that show the field direction at any point. Intensity can also be indicated, by using more closely spaced lines for strong fields, but it is difficult to do this quantitatively where three-dimensional situations are being illustrated on two-dimensional media.

1.1.1 Vector addition

Vector addition (Figure 1.1) must be used when combining fields from different sources. In passive methods, knowledge of the principles of vector addition is needed to understand the ways in which measurements of local anomalies are affected by regional backgrounds. In active methods, a local anomaly (*secondary* field) is often superimposed on a *primary* field produced by a transmitter. In either case, if the local field is much the weaker of the two (in practice, less than one-tenth the strength of the primary or background field), then the measurement will, to a first approximation, be made in the direction of the stronger field and only the component in this direction of the secondary field (c_a in Figure 1.1) will be measured. In most surveys the slight difference in direction between the resultant and the background or primary field can be ignored.

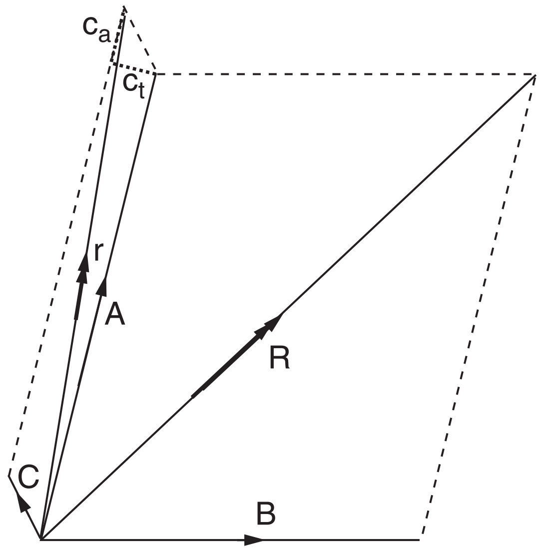


***Figure 1.1** Vector addition by the parallelogram rule. Fields represented in magnitude and direction by the vectors A and B combine to give the resultant R. The resultant* **r** *of A and the smaller field C is approximately equal in length to the sum of A and the component c_a of C in the direction of A. The transverse component c_t rotates the resultant but has little effect on its magnitude.*

If the two fields are similar in strength, there will be no simple relationship between the magnitude of the anomalous field and the magnitude of the observed anomaly. However, variations in any given *component* of the secondary field can be estimated by taking all measurements in an appropriate direction and assuming that the component of the background or primary field in this direction is constant over the survey area. Measurements of vertical rather than total fields are sometimes preferred in magnetic and electromagnetic surveys for this reason.

The fields due to multiple sources are not necessarily equal to the vector sums of the fields that would have existed had those sources been present in isolation. A strong magnetic field from one body can affect the magnetization in another, or even in itself (*demagnetization effect*), and the interactions between fields and currents in electrical and electromagnetic surveys can be very complex.

1.1.2 The inverse-square law

Inverse-square law attenuation of signal strength occurs in most branches of applied geophysics. It is at its simplest in gravity work, where the field due to a point mass is inversely proportional to the square of the distance from the mass, and the constant of proportionality (the *gravitational constant G*) is invariant. Magnetic fields also obey an inverse-square law. The fact that their strength is, in principle, modified by the permeability of the medium is irrelevant in most geophysical work, where measurements are made in either air or water. Magnetic sources are, however, essentially bipolar, and the modifications to the simple inverse-square law due to this fact are much more important (Section 1.1.5).

Electric current flowing from an isolated point electrode embedded in a continuous homogeneous ground provides a physical illustration of the

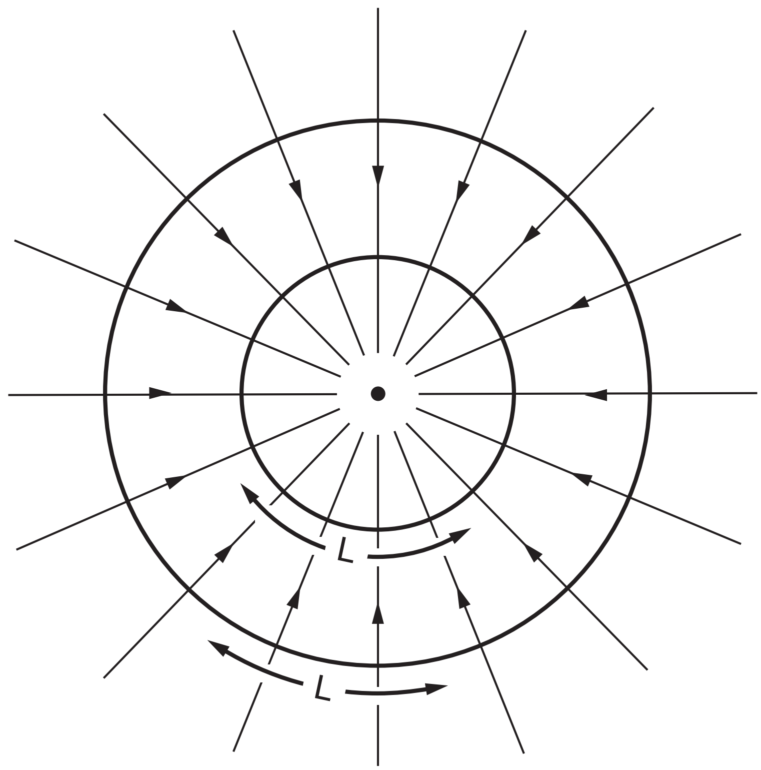


Figure 1.2 *Lines of force from an infinite line source (viewed end on). The distance between the lines increases linearly with distance from the source so that an arc of length L on the inner circle is cut by four lines but an arc of the same length on the outer circle, with double the radius, is cut by only two.*

significance of the inverse-square law. All of the current leaving the electrode must cross any closed surface that surrounds it. If this surface is a sphere concentric with the electrode, the same fraction of the total current will cross each unit area on the surface of the sphere. The current *per unit area* will therefore be inversely proportional to the *total* surface area, which is in turn proportional to the square of the radius. Current flow in the real Earth is, of course, drastically modified by conductivity variations.

1.1.3 Two-dimensional sources

Rates of decrease in field strengths depend on source shapes as well as on the inverse-square law. Infinitely long sources of constant cross-section are termed *two-dimensional (2D)* and are often used in computer modelling to approximate bodies of large strike extent. If the source 'point' in Figure 1.2 represents an infinite line source seen end on, the area of the enclosing (cylindrical) surface is proportional to the radius. The argument applied in the previous section to a point source implies that in this case the field strength is inversely proportional to distance and not to its square. In 2D situations, lines of force drawn on pieces of paper illustrate field magnitude (by their separation) as well as direction.

1.1.4 One-dimensional sources

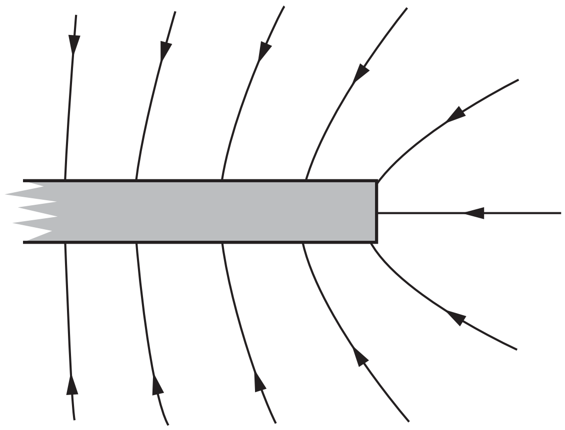


__Figure 1.3__ Lines of force from a semi-infinite slab. The lines diverge appreciably only near the edge of the slab, implying that towards the centre of the slab the field strength will decrease negligibly with distance.

The lines of force or radiation intensity from a source consisting of a homogeneous layer of constant thickness diverge only near its edges (Figure 1.3). The *Bouguer plate* of gravity reductions (Section 2.5.1) and the radioactive source with 2π *geometry* (Section 4.3.3) are examples of infinitely extended layer sources, for which field strengths are independent of distance. This condition is approximately achieved if a detector is only a short distance above an extended source and a long way from its edges.

1.1.5 Dipoles

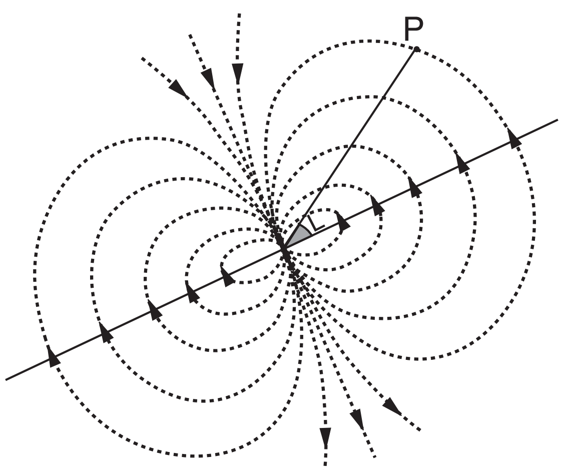


__Figure 1.4__ The dipole field. The plane through the dipole at right angles to its axis is known as the equatorial plane, and the angle (L) between this plane and the line joining the centre of the dipole to any point (P) is sometimes referred to as the latitude of P.

A dipole consists of equal-strength positive and negative point sources a very small distance apart. Field strength decreases as the inverse cube of distance and both strength and direction change with 'latitude' (Figure 1.4). The intensity of the field at a point on a dipole axis is double the intensity at a point the same distance away on the dipole 'equator', and in the opposite direction.

Electrodes are used in some electrical surveys in approximately dipolar pairs and magnetization is fundamentally dipolar. Electric currents circulating in small loops are dipolar sources of magnetic field.

1.1.6 Exponential decay

Radioactive particle fluxes and seismic and electromagnetic waves are subject to absorption as well as geometrical attenuation, and the energy crossing

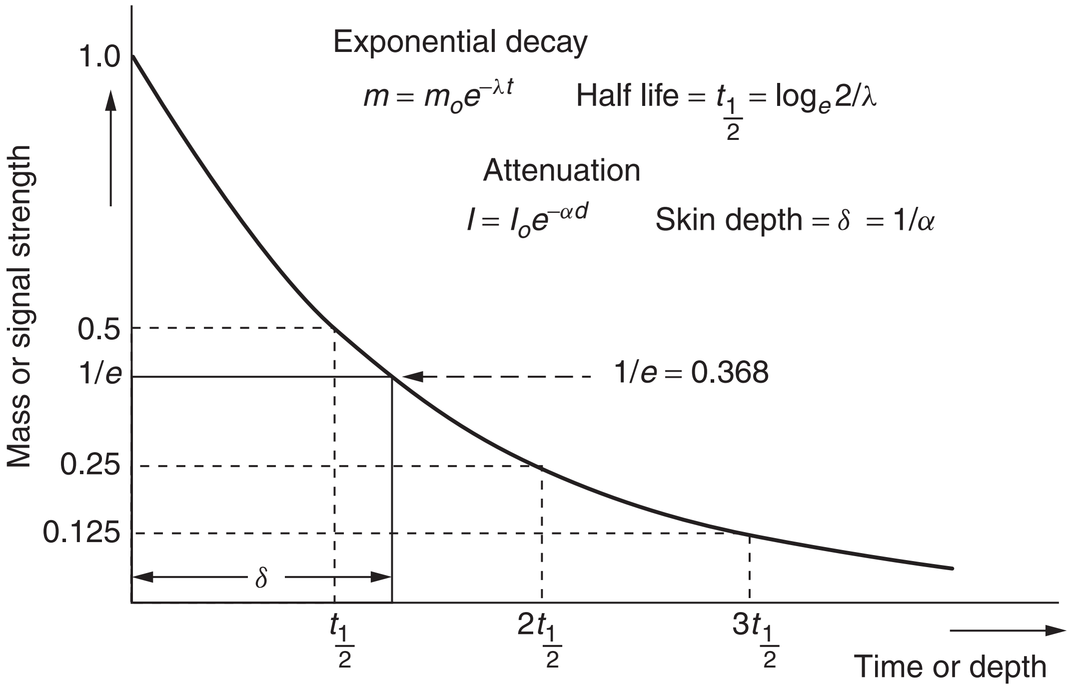


Figure 1.5 *The exponential law, illustrating the parameters used to characterize radioactive decay and radio wave attenuation.*

closed surfaces is then less than the energy emitted by the sources they enclose. In homogeneous media, the percentage loss of signal is determined by the path length and the *attenuation constant*. The absolute loss is proportional also to the signal strength. A similar *exponential* law (Figure 1.5), governed by a *decay constant*, determines the rate of loss of mass by a radioactive substance.

Attenuation rates are alternatively characterized by *skin depths*, which are the reciprocals of attenuation constants. For each skin depth travelled, the signal strength decreases to $1/e$ of its original value, where e (= 2.718) is the base of natural logarithms. Radioactivity decay rates are normally described in terms of the *half-lives*, equal to $\log_e 2$ (= 0.693) divided by the decay constant. During each half-life period, one half of the material present at its start is lost.

1.2 Geophysical Fieldwork

Geophysical instruments vary widely in size and complexity but all are used to make physical measurements, of the sort commonly made in laboratories, at temporary sites in sometimes hostile conditions. They should be economical in power use, portable, rugged, reliable and simple. These criteria are satisfied to varying extents by the commercial equipment currently available.

1.2.1 Choosing geophysical instruments

Few instrument designers can have tried using their own products for long periods in the field, since operator comfort seldom seems to have been considered. Moreover, although many real improvements have been made in the last 30 years, design features have been introduced during the same period, for no obvious reasons, that have actually made fieldwork more difficult. The proton magnetometer staff, discussed below, is a case in point.

If different instruments can, in principle, do the same job to the same standards, practical considerations become paramount. Some of these are listed below.

Serviceability: Is the manual comprehensive and comprehensible? Is a breakdown likely to be repairable in the field? Are there facilities for repairing major failures in the country of use or would the instrument have to be sent overseas, risking long delays en route and in customs? Reliability is vital but some manufacturers seem to use their customers to evaluate prototypes.

Power supplies: If dry batteries are used, are they of types easy to replace or will they be impossible to find outside major cities? If rechargeable batteries are used, how heavy are they? In either case, how long will the batteries last at the temperatures expected in the field? Note that battery life is reduced in cold climates. The reduction can be dramatic if one of the functions of the battery is to keep the instrument at a constant temperature.

Data displays: Are these clearly legible under all circumstances? A torch is needed to read some in poor light and others are almost invisible in bright sunlight. Large displays used to show continuous traces or profiles can exhaust power supplies very quickly.

Hard copy: If hard copy records can be produced directly from the field instrument, are they of adequate quality? Are they truly permanent, or will they become illegible if they get wet, are abraded or are exposed to sunlight?

Comfort: Is prolonged use likely to cripple the operator? Some instruments are designed to be suspended on a strap passing across the back of the neck. This is tiring under any circumstances and can cause serious medical problems if the instrument has to be levelled by bracing it against the strap. Passing the strap over one shoulder and under the other arm may reduce the strain but not all instruments are easy to use when carried in this way.

Convenience: If the instrument is placed on the ground, will it stand upright? Is the cable then long enough to reach the sensor in its normal operating position? If the sensor is mounted on a tripod or pole, is this strong enough? The traditional proton magnetometer poles, in sections that screwed together and ended in spikes that could be stuck into soft ground, have now been largely replaced by unspiked hinged rods that are more awkward to stow away, much more fragile (the hinges can twist and break), can only be used if fully extended and must be supported at all times.

Fieldworthiness: Are the control knobs and connectors protected from accidental impact? Is the casing truly waterproof? Does protection from damp grass depend on the instrument being set down in a certain way? Are there depressions on the console where moisture will collect and then inevitably seep inside?

Automation: Computer control has been introduced into almost all the instruments in current production (although older, less sophisticated models are still in common use). Switches have almost vanished, and every instruction has to be entered via a keypad. This has reduced the problems that used to be caused by electrical spikes generated by switches but, because the settings are often not permanently visible, unsuitable values may be repeatedly used in error. Moreover, simple operations have sometimes been made unduly complicated by the need to access nested menus. Some instruments do not allow readings to be taken until line and station numbers have been entered and some even demand to know the distance to the next station and to the next line!

The computer revolution has produced real advances in field geophysics, but it has its drawbacks. Most notably, the ability to store data digitally in data loggers has discouraged the making of notes on field conditions where these, however important, do not fall within the restricted range of options the logger provides. This problem is further discussed in Section 1.3.2.

1.2.2 Cables

Almost all geophysical work involves cables, which may be short, linking instruments to sensors or batteries, or hundreds of metres long. Electrical induction between cables (electromagnetic coupling, also known as *cross-talk*) can be a serious source of noise (see also Section 11.3.5).

Efficiency in cable handling is an absolute necessity. Long cables always tend to become tangled, often because of well-intentioned attempts to make neat coils using hand and elbow. Figures of eight are better than simple loops, but even so it takes an expert to construct a coil from which cable can be run freely once it has been removed from the arm. On the other hand, a seemingly chaotic pile of wire spread loosely on the ground can be quite trouble-free. The basic rule is that cable must be fed on and off the pile in opposite directions, i.e. the last bit of cable fed on must be the first to be pulled off. Any attempts to pull cable from the bottom will almost certainly end in disaster.

Cable piles are also unlikely to cause the permanent kinks which are often features of neat and tidy coils and which may have to be removed by allowing the cable to hang freely and untwist naturally. Places where this is possible with 100-metre lengths are rare.

Piles can be made portable by feeding cables into open boxes, and on many seismic surveys the shot-firers carried their firing lines in this way in old gelignite boxes. Ideally, however, if cables are to be carried from place to place, they should be wound on properly designed drums. Even then, problems can occur. If cable is unwound by pulling on its free end, the drum will not stop simply because the pull stops, and a free-running drum is an effective, but untidy, knitting machine.

A drum carried as a back-pack should have an efficient brake and should be reversible so that it can be carried across the chest and be wound from a standing position. Some drums sold with geophysical instruments combine total impracticality with inordinate expense and are inferior to home-made or garden-centre versions.

Geophysical lines exert an almost hypnotic influence on livestock. Cattle have been known to desert lush pastures in favour of midnight treks through hedges and across ditches in search of juicy cables. Not only can a survey be delayed but a valuable animal may be killed by biting into a live conductor, and constant vigilance is essential.

1.2.3 Connections

Crocodile clips are usually adequate for electrical connections between single conductors. Heavy plugs must be used for multi-conductor connections and are usually the weakest links in the entire field system. They should be placed on the ground very gently and as seldom as possible and, if they do not have screw-on caps, be protected with plastic bags or ‘clingfilm’. They must be shielded from grit as well as moisture. Faults are often caused by dirt increasing wear on the contacts in socket units, which are almost impossible to clean.

Plugs should be clamped to their cables, since any strain will otherwise be borne by the weak soldered connections to the individual pins. Inevitably, the cables are flexed repeatedly just beyond the clamps, and wires may break within the insulated sleeving at these points. Any break there, or a broken or dry joint inside the plug, means work with a soldering iron. This is never easy when connector pins are clotted with old solder, and is especially difficult if many wires crowd into a single plug.

Problems with plugs can be minimized by ensuring that, when moving, they are always carried, never dragged along the ground. Two hands should always be used, one holding the cable to take the strain of any sudden pull, the other to support the plug itself. The rate at which cable is reeled in should never exceed a comfortable walking pace, and especial care is needed when the last few metres are being wound on to a drum. Drums should be fitted with clips or sockets where the plugs can be secured when not in use.

1.2.4 Geophysics in the rain

A geophysicist, huddled over his instruments, is a sitting target for rain, hail, snow and dust, as well as mosquitoes, snakes and dogs. His most useful piece of field clothing is often a large waterproof cape which he can not only wrap around himself but into which he can retreat, along with his instruments, to continue work (Figure 1.6).

Electrical methods that rely on direct or close contact with the ground generally do not work in the rain, and heavy rain can be a source of seismic noise. Other types of survey can continue, since most geophysical instruments are supposed to be waterproof and some actually are. However, unless dry weather can be guaranteed, a field party should be plentifully supplied with plastic bags and sheeting to protect instruments, and paper towels for

Figure 1.6 *The geophysical cape in action. Magnetometer and observer are both dry, with only the sensor bottle exposed to the elements.*

drying them. Large transparent plastic bags can often be used to enclose instruments completely while they are being used, but even then condensation may create new conductive paths, leading to drift and erratic behaviour. Silica gel within instruments can absorb minor traces of moisture but cannot cope with large amounts, and a portable hair-drier held at the base camp may be invaluable.

1.2.5 A geophysical toolkit

Regardless of the specific type of geophysical survey, similar tools are likely to be needed. A field toolkit should include the following:

- Long-nose pliers (the longer and thinner the better)
- Slot-head screwdrivers (one very fine, one normal)
- Phillips screwdriver
- Allen keys (metric and imperial)
- Scalpels (light, expendable types are best)
- Wire cutters/strippers
- Electrical contact cleaner (spray)
- Fine-point 12V soldering iron
- Solder and ‘Solder-sucker’
- Multimeter (mainly for continuity and battery checks, so small size and durability are more important than high sensitivity)
- Torch (preferably of a type that will stand unsupported and double as a table lamp. A ‘head torch’ can be very useful)
- Hand lens
- Insulating tape, preferably self-amalgamating
- Strong epoxy glue/‘super-glue’
- Silicone grease
- Waterproof sealing compound
- Spare insulated and bare wire, and connectors
- Spare insulating sleeving
- Kitchen cloths and paper towels
- Plastic bags and ‘clingfilm’

A comprehensive first-aid kit is equally vital.

1.3 Geophysical Data

Some geophysical readings are of true *point data* but others are obtained using sources that are separated from detectors. Where values are determined *between* rather than *at* points, readings will be affected by orientation. Precise field notes are always important but especially so in these cases, since reading points must be defined and orientations must be recorded.

If transmitters, receivers and/or electrodes are laid out in straight lines and the whole system can be reversed without changing the reading, the mid-point should be considered the reading point. Special notations are needed for asymmetric systems, and the increased probability of positioning error is in itself a reason for avoiding asymmetry. Especial care must be taken when recording the positions of sources and detectors in seismic work.

1.3.1 Station numbering

Station numbering should be logical and consistent. Where data are collected along traverses, numbers should define positions in relation to the traverse grid. Infilling between traverse stations 3 and 4 with stations $3\frac{1}{4}$, $3\frac{1}{2}$ and $3\frac{3}{4}$ is clumsy and may create typing problems, whereas defining as 325E a station halfway between stations 300E and 350E, which are 50 metres apart, is easy and unambiguous. The fashion for labelling such a station 300+25E has no discernible advantages and uses a plus sign which may be needed, with digital field systems or in subsequent processing, to stand for N or E. It may be worth defining the grid origin in such a way that S or W stations do not occur, and this may be essential with data loggers that cannot cope with either negatives or points of the compass.

Stations scattered randomly through an area are best numbered sequentially. Positions can be recorded in the field by pricking through maps or air-photos and labelling the reverse sides. Estimating coordinates in the field from maps may seem desirable but mistakes are easily made and valuable time is lost. Station coordinates are now often obtained from GPS receivers (Section 1.5), but differential GPS may be needed to provide sufficient accuracy for detailed surveys.

If several observers are involved in a single survey, numbers can easily be accidentally duplicated. All field books and sheets should record the name of the observer. The interpreter or data processor will need to know who to look for when things go wrong.

1.3.2 Recording results

Geophysical results are primarily numerical and must be recorded even more carefully than qualitative observations of field geology. Words, although sometimes difficult to read, can usually be deciphered eventually, but a set of numbers may be wholly illegible or, even worse, may be misread. The need for extra care has to be reconciled with the fact that geophysical observers are usually in more of a hurry than are geologists, since their work may involve instruments that are subject to drift, draw power from batteries at frightening speed or are on hire at high daily rates.

Numbers may, of course, not only be misread but miswritten. The circumstances under which data are recorded in the field are varied but seldom ideal. Observers are usually either too hot, too cold, too wet or too thirsty. Under such conditions, they may delete correct results and replace them with incorrect ones, in moments of confusion or temporary dyslexia. Data on geophysical field sheets should therefore never be erased. Corrections should be made by crossing out the incorrect items, preserving their legibility, and writing the correct values alongside. Something may then be salvaged even if the correction is wrong. Precise reporting standards must be enforced and strict routines must be followed if errors are to be minimized. Reading the instrument twice at each occupation of a station, and recording both values, reduces the incidence of major errors.

Loss of geophysical data tends to be final. Some of the qualitative observations in a geological notebook might be remembered and re-recorded, but not strings of numbers. Copies are therefore essential and should be made in the field, using duplicating sheets or carbon paper, or by transcribing the results each evening. Whichever method is used, originals and duplicates must be separated immediately and stored separately thereafter. Duplication is useless if copies are stored, and lost, together. This, of course, applies equally to data stored in a data logger incorporated in, or linked to, the field instrument. Such data should be checked, and backed up, each evening.

Digital data loggers are usually poorly adapted to storing non-numeric information, but observers are uniquely placed to note and comment on a multitude of topographic, geological, manmade (*cultural*) and climatic factors that may affect the geophysical results. If they fail to do so, the data that they have gathered may be interpreted incorrectly. If data loggers are not being used, comments should normally be recorded in notebooks, alongside the readings concerned. If they are being used, adequate supplementary positional data must be stored elsewhere. In archaeological and site investigation surveys, where large numbers of readings are taken in very small areas, annotated sketches are always useful and may be essential. Sketch maps should be made wherever the distances of survey points or lines from features in the environment are important. Geophysical field workers may also have a responsibility to pass on to their geological colleagues information of interest about places that only they may visit. They should at least be willing to record dips and strikes, and perhaps to return with rock samples where these would be useful.

1.3.3 Accuracy, sensitivity, precision

Accuracy must be distinguished from sensitivity. A standard gravity meter, for example, is sensitive to field changes of one-tenth of a gravity unit but an equivalent level of accuracy will be achieved only if readings are carefully made and drift and tidal corrections are correctly applied. Accuracy is thus limited, but not determined, by instrument sensitivity. Precision, which is concerned only with the numerical presentation of results (e.g. the number of decimal places used), should always be appropriate to accuracy (Example 1.1). Not only does superfluous precision waste time but false conclusions may be drawn from the high implied accuracy.

Example 1.1

Gravity reading = 858.3 scale units

Calibration constant = 1.0245 g.u. per scale division (see Section 2.1)

Converted reading = 879.32835 g.u.

But reading accuracy is only 0.1 g.u. (approximately), and therefore:

Converted reading = 879.3 g.u.

(Four decimal place precision is needed in the calibration constant, because 858.3 multiplied by 0.0001 is equal to almost 0.1 g.u.)

Geophysical measurements can sometimes be made to a greater accuracy than is needed, or even usable, by the interpreters. However, the highest possible accuracy should always be sought, as later advances may allow the data to be analysed more effectively.

1.3.4 Drift

A geophysical instrument will usually not record the same results if read repeatedly at the same place. This may be due to changes in background field but can also be caused by changes in the instrument itself, i.e. to *drift*. Drift correction is often the essential first stage in data analysis, and is usually based on repeat readings at *base stations* (Section 1.4).

Instrument drift is often related to temperature and is unlikely to be linear between two readings taken in the relative cool at the beginning and end of a day if temperatures are 10 or 20 degrees higher at noon. Survey *loops* may therefore have to be limited to periods of only one or two hours.

Drift calculations should be made whilst the field crew is still in the survey area so that readings may be repeated if the drift-corrected results appear questionable. Changes in background field are sometimes treated as drift but in most cases the variations can either be monitored directly (as in magnetics) or calculated (as in gravity). Where such alternatives exist, it is preferable they be used, since poor instrument performance may otherwise be overlooked.

1.3.5 Signal and noise

To a geophysicist, *signal* is the object of the survey and *noise* is anything else that is measured but is considered to contain no useful information. One observer's signal may be another's noise. The magnetic effect of a buried pipe is a nuisance when interpreting magnetic data in geological terms but may be invaluable to a site developer. Much geophysical field practice is dictated by the need to improve signal-to-noise ratios. In many cases, as in magnetic surveys, variations in a background field are a source of noise and must be precisely monitored.

The statistics of random noise are important in seismic, radiometric and induced polarization (IP) surveys. Adding together N statistically long random series, each of average amplitude A, produces a random series with average amplitude $A \times \sqrt{N}$. Since N identical signals of average amplitude A treated in the same way produce a signal of amplitude $A \times N$, adding together (*stacking*) N signals containing some random noise should improve signal-to-noise ratios by a factor of $\sqrt{N}$.

1.3.6 Variance and standard deviation

Random variations often follow a *normal* or *Gaussian* distribution law, described by a bell-shaped probability curve. Normal distributions can be characterized by *means* (equal to the sums of all the values divided by the total number of values) and *variances* (defined in Figure 1.7) or their square-roots, the *standard deviations* (SD). About two-thirds of the readings in a

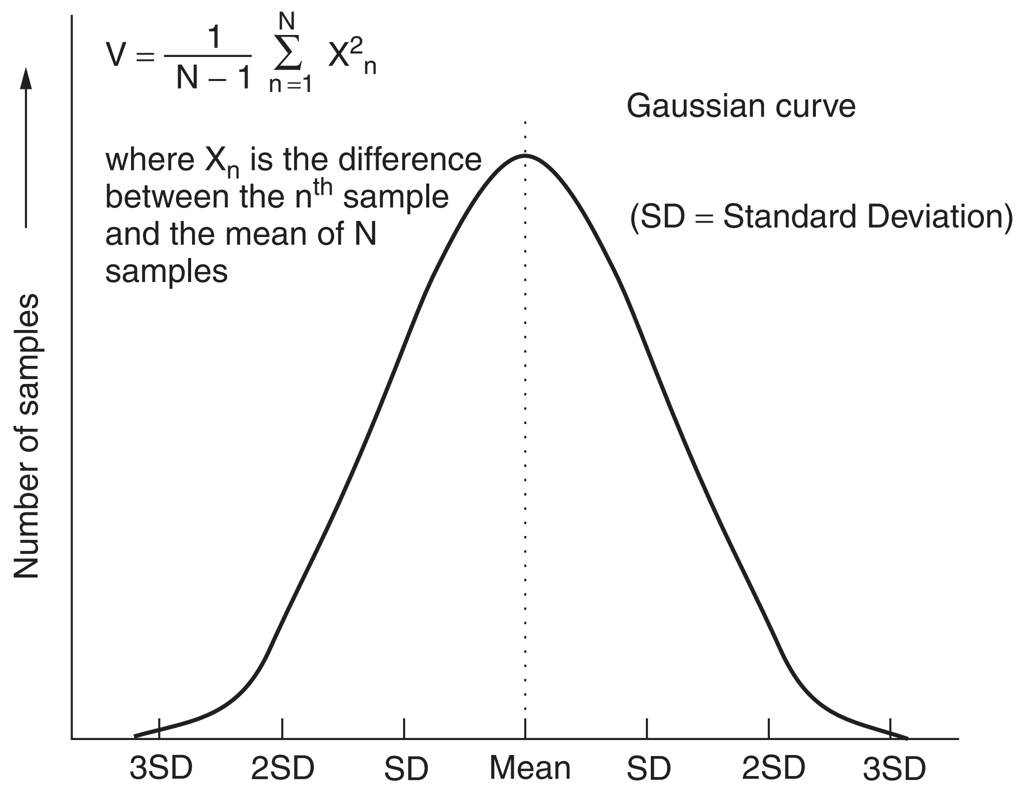


Figure 1.7 *Gaussian distribution. The curve is symmetric, and approximately two-thirds of the area beneath it (i.e. two-thirds of the total number of samples) lies within one standard deviation (SD) of the mean.*

normal distribution lie within 1 SD of the mean, and less than 0.3% differ from it by more than 3 SDs. The SD is popular with contractors when quoting survey reliability, since a small value can efficiently conceal several major errors. Geophysical surveys rarely provide enough field data for statistical methods to be validly applied, and distributions are more often assumed to be normal than proven to be so.

1.3.7 Anomalies

Only rarely is a single geophysical observation significant. Usually, many readings are needed, and regional background levels must be determined, before interpretation can begin. Interpreters tend to concentrate on *anomalies*, i.e. on differences from a constant or smoothly varying background. Geophysical anomalies take many forms. A massive sulphide deposit containing pyrrhotite would be dense, magnetic and electrically conductive. Typical anomaly profiles recorded over such a body by various types of geophysical survey are shown in Figure 1.8. A wide variety of possible contour patterns correspond to these differently shaped profiles.

Background fields also vary and may, at different scales, be regarded as anomalous. A ‘mineralization’ gravity anomaly, for example, might lie on a broader high due to a mass of basic rock. Separation of regionals from residuals is an important part of geophysical data processing and even in the field it may be necessary to estimate background so that the significance of local anomalies can be assessed. On profiles, background fields estimated by eye may be more reliable than those obtained using a computer, because of the virtual impossibility of writing a computer program that will produce a background field uninfluenced by the anomalous values (Figure 1.9). Computer methods are, however, essential when deriving backgrounds from data gathered over an area rather than along a single line.

The existence of an anomaly indicates a difference between the real world and some simple model, and in gravity work the terms *free air*, *Bouguer* and *isostatic anomaly* are commonly used to denote derived quantities that represent differences from gross Earth models. These so-called anomalies are sometimes almost constant within a small survey area, i.e. the area is not anomalous! Use of terms such as Bouguer *gravity* (rather than Bouguer anomaly) avoids this confusion.

1.3.8 Wavelengths and half-widths

Geophysical anomalies in profile often resemble transient waves but vary in space rather than time. In describing them the terms *frequency* and *frequency content* are often loosely used, although *wavenumber* (the number of complete waves in unit distance) is pedantically correct. *Wavelength* may be quite properly used of a spatially varying quantity, but is imprecise where

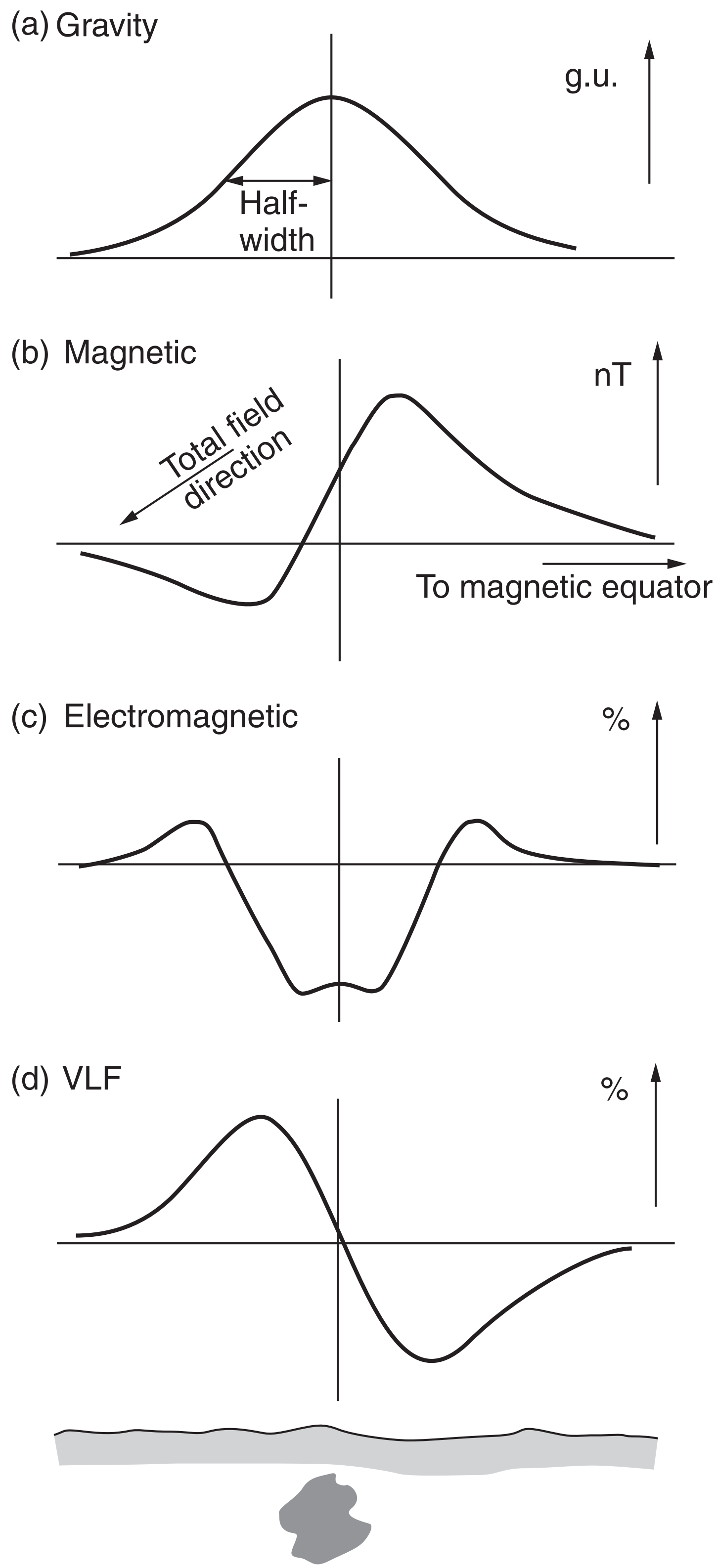


Figure 1.8 *Geophysical profiles across a pyrrhotite-bearing sulphide mass. The amplitude of the gravity anomaly (a) might be a few g.u. and of the magnetic anomaly (b) a few hundred nT. The electromagnetic anomalies are for (c) a two-coil co-planar system and (d) a VLF dip-angle system. Neither of these is likely to have an amplitude of more than about 20%.*

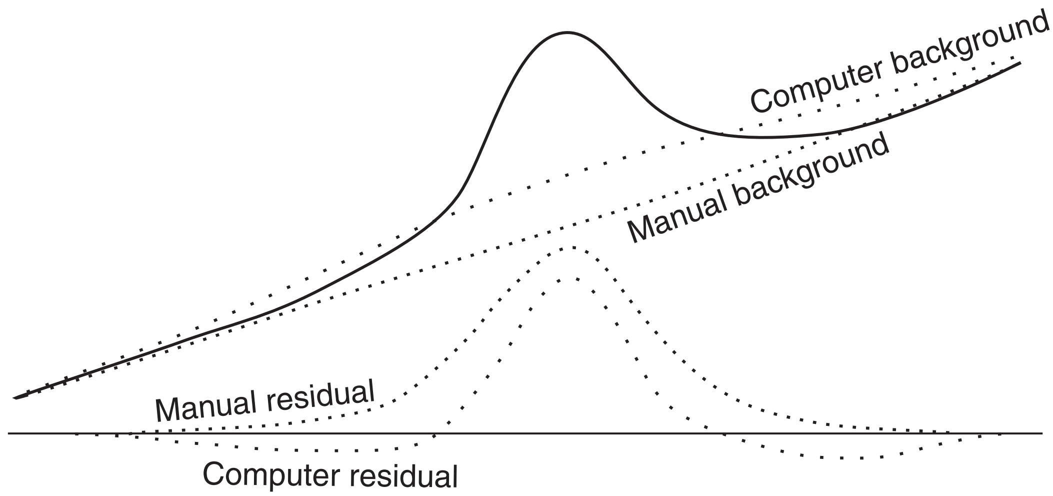


Figure 1.9 *Computer and manual residuals. The background field drawn by eye recognizes the separation between regional and local anomaly, and the corresponding residual anomaly is probably a good approximation to the actual effect of the local source. The computer-drawn background field is biased by the presence of the local anomaly, and the corresponding residual anomaly is therefore flanked by troughs.*

geophysical anomalies are concerned because an anomaly described as having a single 'wavelength' would be resolved by Fourier analysis into a number of components of different wavelengths.

A more easily estimated quantity is the *half-width*, which is equal to half the distance between the points at which the amplitude has fallen to half the anomaly maximum (cf. Figure 1.8a). This is roughly equal to a quarter of the wavelength of the dominant sinusoidal component, but has the advantage of being directly measurable on field data. Wavelengths and half-widths are important because they are related to the depths of sources. Other things being equal, the deeper the source, the broader the anomaly.

1.3.9 Presentation of results

The results of surveys along traverse lines can be presented in profile form, as in Figure 1.8. It is usually possible to plot profiles in the field, or at least each evening, as work progresses, and such plots are vital for quality control. A laptop computer can reduce the work involved, and many modern instruments and data loggers are programmed to display profiles in 'real time' as work proceeds.

A traverse line drawn on a topographic map can be used as the baseline for a geophysical profile. This type of presentation is particularly helpful in identifying anomalies due to manmade features, since correlations with features such as roads and field boundaries are obvious. If profiles along a number of different traverses are plotted in this way on a single map they are said to be *stacked*, a word otherwise used for the addition of multiple data sets to form a single output set (see Section 1.3.5).

Contour maps used to be drawn in the field only if the strike of some feature had to be defined quickly so that infill work could be planned, but once again the routine use of laptop computers has vastly reduced the work involved. However, information is lost in contouring because it is not generally possible to choose a contour interval that faithfully records all the features of the original data. Also, contour lines are drawn in the areas between traverses, where there are no data, and inevitably introduce a form of noise. Examination of contour patterns is not, therefore, the complete answer to field quality control.

Cross-sectional contour maps (*pseudo-sections*) are described in Sections 6.3.5 and 7.4.2.

In engineering site surveys, pollution monitoring and archaeology, the objects of interest are generally close to the surface and their positions in plan are usually much more important than their depths. They are, moreover, likely to be small and to produce anomalies detectable only over very small areas. Data have therefore to be collected on very closely spaced grids and can often be presented most effectively if background-adjusted values are used to determine the colour or grey-scale shades of picture elements (*pixels*) that can be manipulated by image-processing techniques. Interpretation then relies on pattern recognition and a single pixel value is seldom important. Noise is eliminated by eye, i.e. patterns such as those in Figure 1.10 are easily recognized as due to human activity.

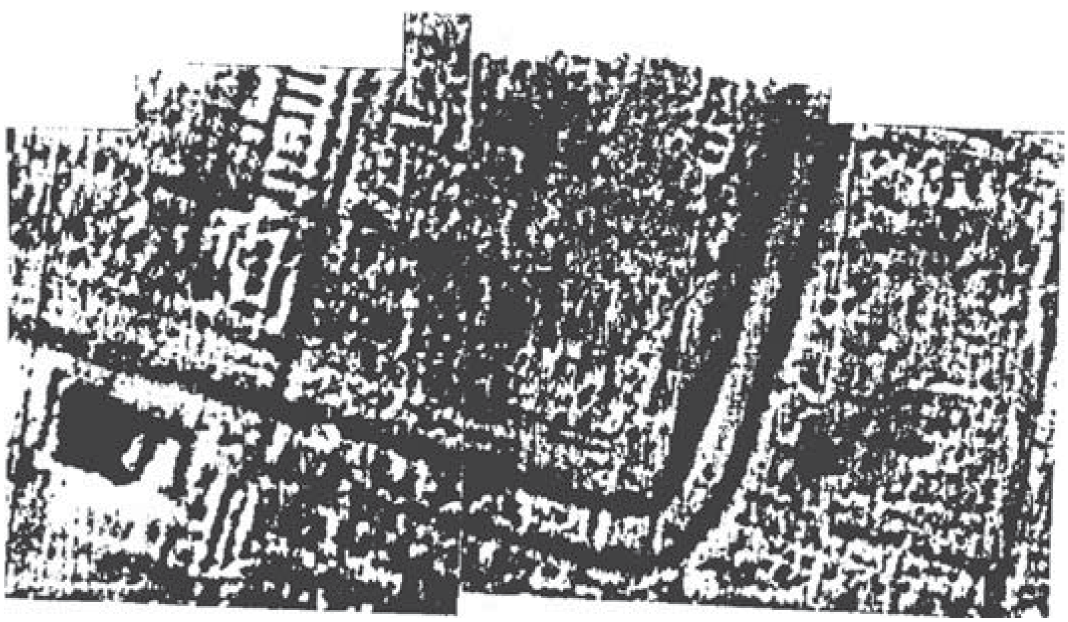


Figure 1.10 *Image-processed magnetic data over an archaeological site. (Reproduced by permission of Professor Irwin Scollar.)*

1.3.10 Data loggers

During the past decade, automation of geophysical equipment in small-scale surveys has progressed from a rarity to a fact of life. Although many of the older types of instrument are still in use, and giving valuable service, they now compete with variants containing the sort of computer power employed, 30 years ago, to put a man on the moon. At least one manufacturer now proudly boasts 'no notebook', even though the instrument in question is equipped with only a numerical key pad so that there is no possibility of entering text comments into the (more than ample) memory. On other automated instruments the data display is so small and so poorly positioned that the possibility that the observer might actually want to look at, and even think about, his observations as he collects them has clearly not been considered. Unfortunately, this pessimism may all too often be justified, partly because of the speed with which readings, even when in principle discontinuous, can now be taken and logged. Quality control thus often depends on the subsequent playback and display of whole sets of data, and it is absolutely essential that this is done on, at the most, a daily basis. As Oscar Wilde might have said (had he opted for a career in field geophysics), to spend a few hours recording rubbish might be accounted a misfortune. To spend anything more than a day doing so looks suspiciously like carelessness.

Automatic data loggers, whether 'built-in' or separate, are particularly useful where instruments can be dragged, pushed or carried along traverse to provide virtually continuous readings. Often, all that is required of the operators is that they press a key to initiate the reading process, walk along the traverse at constant speed and press the key again when the traverse is completed. On lines more than about 20 m long, additional keystrokes can be used to 'mark' intermediate survey points.

One consequence of continuous recording has been the appearance in ground surveys of errors of types once common in airborne surveys which have now been almost eliminated by improved compensation methods and GPS navigation. These were broadly divided into *parallax* errors, *heading* errors, ground clearance/coupling errors and errors due to speed variations.

With the system shown in Figure 1.11, parallax errors can occur because the magnetic sensor is about a metre ahead of the GPS sensor. Similar errors can occur in surveys where positions are recorded by key strokes on a data logger. If the key is depressed by the operator when he, rather than the sensor, passes a survey peg, all readings will be displaced from their true positions. If, as is normal practice, alternate lines on the grid are traversed in opposite directions, a *herringbone* pattern will be imposed on a linear anomaly, with the position of the peak fluctuating backwards and forwards according to the direction in which the operator was walking (Figure 1.12a).

Figure 1.11 *Magnetometer coupled to a differential GPS navigation system. Unless allowance is made in processing for the offset between the GPS aerial (behind the operator's head) and the magnetometer sensor (at the end of the horizontal bar), anomalies will be incorrectly located on detailed maps (photo courtesy Geometrics Inc.)*

False anomalies can also be produced in airborne surveys if ground clearance is allowed to vary, and similar effects can now be observed in ground surveys. Keeping the sensor shown in Figure 1.11 at a constant height above the ground is not easy (although a light flexible 'spacer' hanging from it can help). On level ground there tends to be a rhythmic effect associated with the operator's motion, and this can sometimes appear on contour maps as 'striping' at right angles to the traverse when minor peaks and troughs on adjacent lines are linked to each other by the contouring algorithm. On slopes there will, inevitably, be a tendency for a sensor in front of the observer to be closer to the ground when going uphill than when going down. How this will affect the final maps will vary with the nature of the terrain, but in an area with constant slope there will a tendency for background levels to be different on parallel lines traversed in opposite directions. This can produce herringbone effects on individual contour lines in low gradient areas (Figure 1.12b).

Heading errors occurred in airborne (especially aeromagnetic) surveys because the effect of the aircraft on the sensor depended on aircraft orientation.

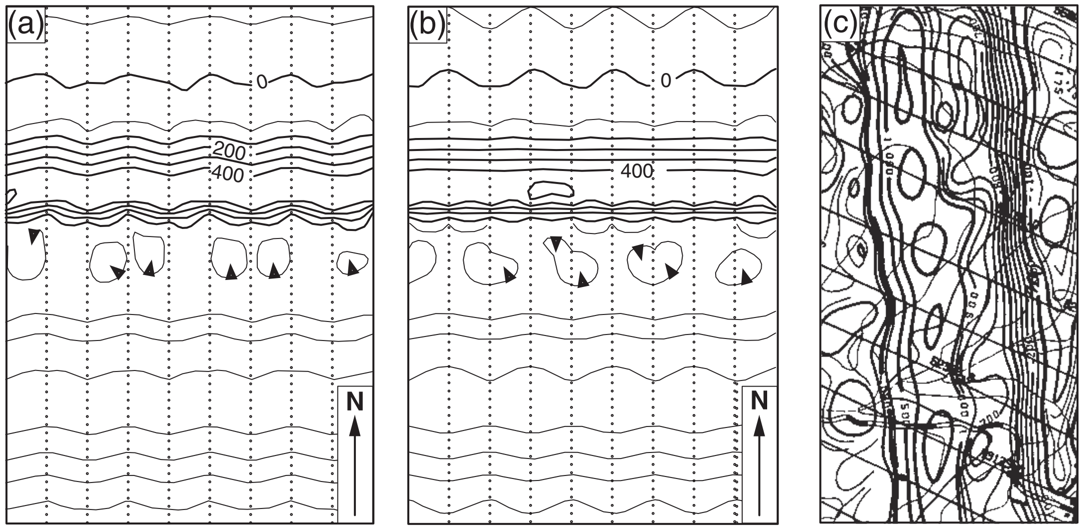


Figure 1.12 *Distortions in automatic contouring of linear anomalies. (a) Herringbone pattern due to a parallax error, i.e. to a consistent offset between geophysical and positional control, with alternate lines measured in opposite directions. (b) Herringbone pattern due to a consistent difference in background levels on lines measured in opposite directions (see discussion in text). Note that in this case the effect is barely visible on the large anomaly indicated by thick contour lines at 100 nT intervals, but is very obvious in the low-gradient areas where contours are shown by thinner lines at 10 and 50 nT intervals. (c) Introduction of closures on the peak of a linear anomaly by an automatic contouring program seeking (as most do) to equalize gradients in all directions. A similar effect can be seen in the 'bubbling' of the very closely spaced contour lines on the south side of the anomaly in (b). In neither case are the features necessitated by the data, which exists only along the traverse lines indicated by points in (b) and continuous lines in (c).*

A similar effect can occur in a ground magnetic survey if the observer is carrying any iron or steel material. The induced magnetization in these objects will vary according to the facing direction, producing effects similar to those produced by constant slopes, i.e. similar to those in Figure 1.12b.

Before the introduction of GPS navigation, flight path recovery in airborne surveys relied on interpolation between points identified photographically. Necessarily, ground speed was assumed constant between these points, and anomalies were displaced if this was not the case. Similar effects can now be seen in datalogged ground surveys. Particularly common reasons for slight displacements of anomalies are that the observer either presses the key to start recording at the start of the traverse, and then starts walking or, at the end of the traverse, stops walking and only then presses the key to stop recording. These effects can be avoided by insisting that observers begin walking before the start of the traverse and continue walking until the end point has been safely passed. If, however, speed changes are due to rugged ground, all that can be done is to increase the number of 'marked' points.

Many data loggers not only record data but have screens large enough to show individual and multiple profiles, allowing a considerable degree of quality control in the field. Further quality control will normally be done each evening, using automatic contouring programs on laptop PCs, but allowance must be made for the fact that automatic contouring programs tend to introduce their own distortions (Figure 1.12c).

1.4 Bases and Base Networks

Bases (*base stations*) are important in gravity and magnetic surveys, and in some electrical and radiometric work. They may be:

1. *Drift bases* – Repeat stations that mark the starts and ends of sequences of readings and are used to control drift.
2. *Reference bases* – Points where the value of the field being measured has already been established.
3. *Diurnal bases* – Points where regular measurements of background are made whilst field readings are taken elsewhere.

A single base may fulfil more than one of these functions. The reliability of a survey, and the ease with which later work can be tied to it, will often depend on the quality of the base stations. Base-station requirements for individual geophysical methods are considered in the appropriate chapters, but procedures common to more than one type of survey are discussed below.

1.4.1 Base station principles

There is no absolute reason why any of the three types of base should coincide, but surveys tend to be simpler and fewer errors are made if every *drift base* is also a *reference base.* If, as is usually the case, there are too few existing reference points for this to be done efficiently, the first step in a survey should be to establish an adequate base network.

It is not essential that the *diurnal base* be part of this network and, because two instruments cannot occupy exactly the same point at the same time, it may actually be inconvenient for it to be so. However, if a diurnal monitor has to be used, work will normally be begun each day by setting it up and end with its removal. It is good practice to read the field instruments at a drift base at or near the monitor position on these occasions, noting any differences between the simultaneous readings of the base and field instruments.

1.4.2 ABAB ties

Bases are normally linked together using ABAB ties (Figure 1.13). A reading is made at Base A and the instrument is then taken as quickly as possible

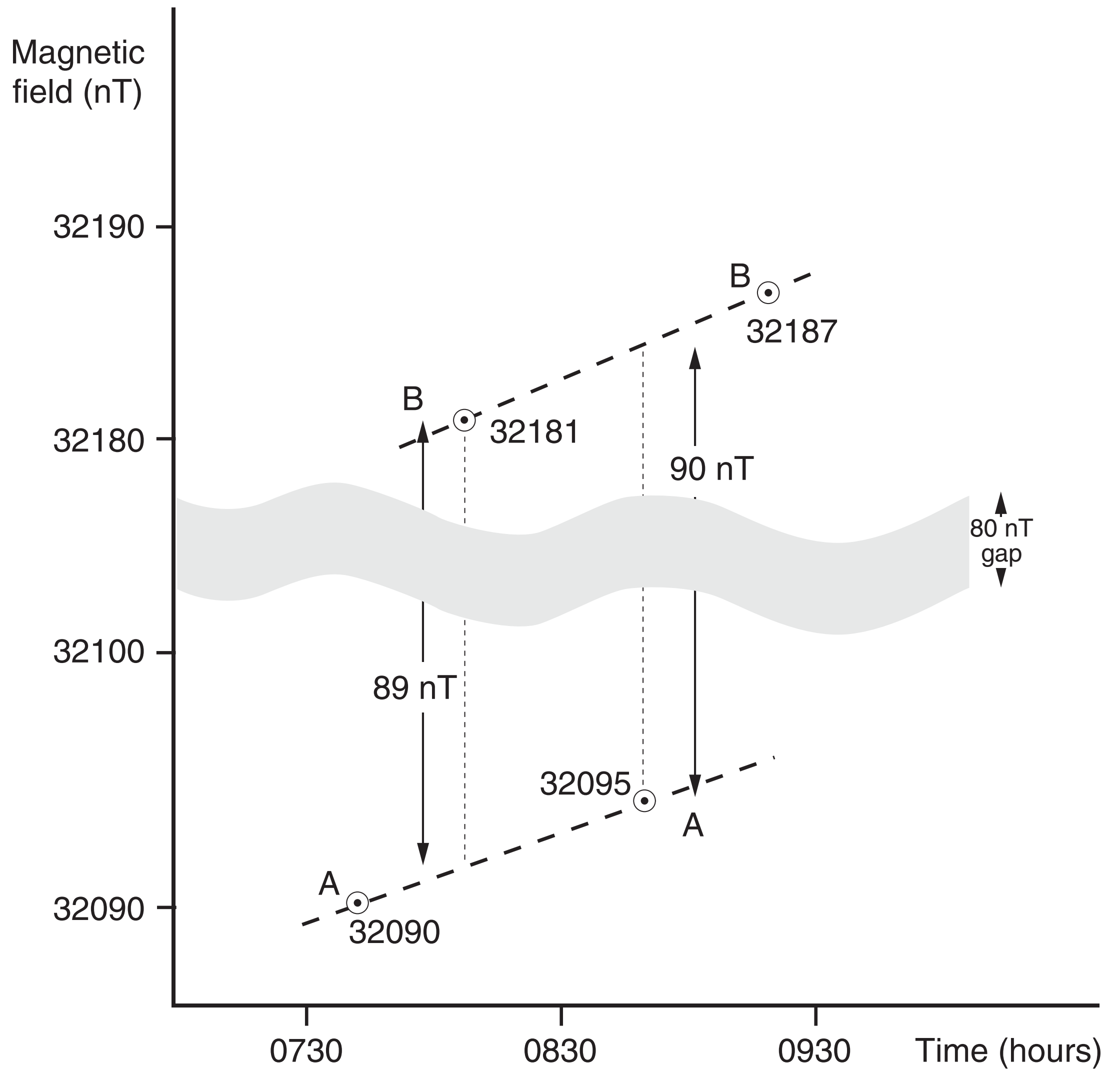


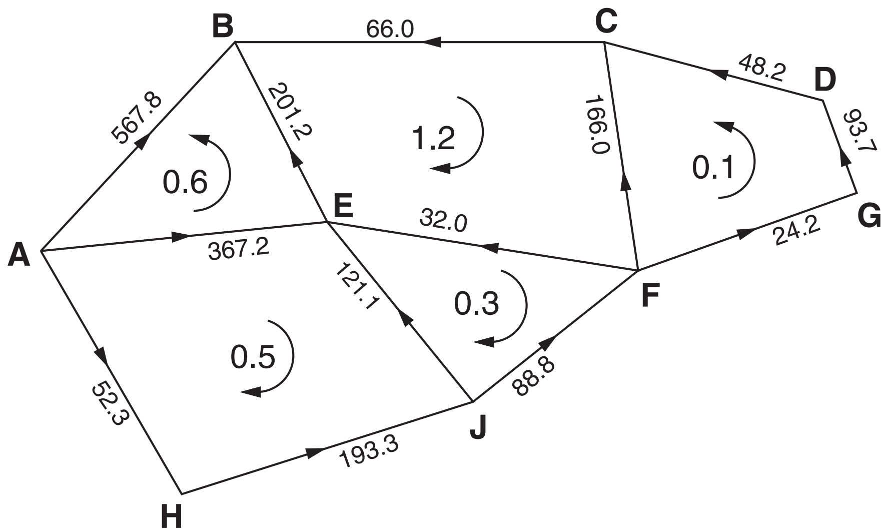
Figure 1.13 *ABAB tie between bases in a magnetic survey with a 1 nT instrument. The estimated difference between the two stations would be 89 nT. Note that the plotting scale should be appropriate to instrument sensitivity and that it may be necessary to 'remove' some of the range of the graph to allow points to be plotted with sufficient precision.*

to Base B. Repeat readings are then made at A and again at B. The times between readings should be short so that drift, and sometimes also diurnal variation, can be assumed linear. The second reading at B may also be the first in a similar set linking B to a Base C, in a process known as *forward looping*.

Each set of four readings provides two estimates of the difference in field strength between the two bases, and if these do not agree within the limits of instrument accuracy (± 1 nT in Figure 1.13), further ties should be made. Differences should be calculated in the field so that any necessary extra links can be added immediately.

1.4.3 Base networks

Most modern geophysical instruments are accurate and quite easy to read, so that the error in any ABAB estimate of the difference in value between two points should be trivial. However, a final value obtained at the end of an extended series of links could include quite large accumulated errors. The integrity of a system of bases can be assured if they form part of a network in which each base is linked to at least two others. *Misclosures* are calculated by summing differences around each loop, with due regard to sign, and are then reduced to zero by making the smallest possible adjustments to individual differences. The network in Figure 1.14 is sufficiently simple to be adjusted



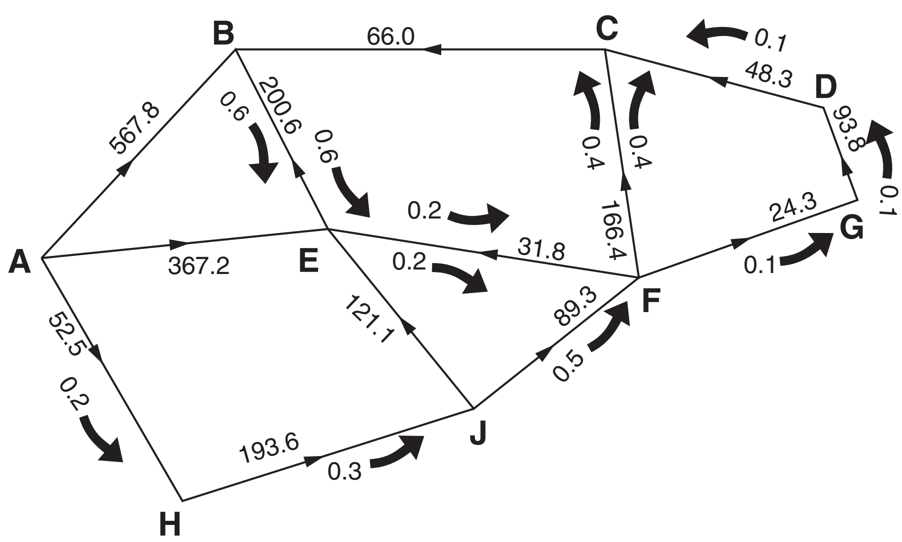


Figure 1.14 *Network adjustment. (a) The 1.2 unit misclosure in loop BCFE suggests a large error in either the 'unsupported' link BC or in BE, the only link shared with another loop with a large misclosure. (b) Adjustments made on the assumption that BC was checked and found to be correct but that no other checks could be made.*

by inspection. A more complicated network could be adjusted by computer, using least-squares or other criteria, but this is not generally necessary in small-scale surveys.

1.4.4 Selecting base stations

It is important that bases be adequately described and, where possible, permanently marked, so that extensions or infills can be linked to previous work by exact re-occupations. Concrete or steel markers can be quickly destroyed, either deliberately or accidentally, and it is usually better to describe station locations in terms of existing features that are likely to be permanent. In any survey area there will be points that are distinctive because of the presence of manmade or natural features. Written descriptions and sketches are the best way to preserve information about these points for the future. Good sketches are usually better than photographs, because they can emphasize salient points.

Permanence can be a problem, e.g. maintaining gravity bases at international airports is almost impossible because building work is almost always under way. Geodetic survey markers are usually secure but may be in isolated and exposed locations. Statues, memorials and historic or religious buildings often provide sites that are not only quiet and permanent but also offer some shelter from sun, wind and rain.

1.5 Global Positioning Satellites

Small, reasonably cheap, hand-held GPS receivers have been available since about 1990. Until May 2000, however, their accuracy was no better than a few hundred metres in position and even less in elevation, because of deliberate signal degradation for military reasons (‘selective availability’ or SA). The instruments were thus useful only for the most regional of surveys. For more accurate work, differential GPS (DGPS) was required, involving a base station and recordings, both in the field and at the base, of the estimated ranges to individual satellites. Transmitted corrections that could be picked up by the field receiver allowed *real-time kinetic positioning (RTKP).* Because of SA, differential methods were essential if GPS positioning was to replace more traditional methods in most surveys, even though the accuracies obtainable in differential mode were usually greater than needed for geophysical purposes.

1.5.1 Accuracies in hand-held GPS receivers

The removal of SA dramatically reduced the positional error in non-differential GPS, and signals also became easier to acquire. It is often now possible to obtain fixes through forest canopy, although buildings or solid rock between receiver and satellite still present insuperable obstacles. The precision of the readouts on small hand-held instruments, for both elevations and co-ordinates, is generally to the nearest metre, or its rough equivalent in latitude and longitude (0.00001°). Accuracies are considerably less, because of *multi-path errors* (i.e. reflections from topography or buildings providing alternative paths of different lengths) and because of variations in the properties of the atmosphere. The main atmospheric effects occur in the ionosphere and depend on the magnitude and variability of the ionization. They are thus most severe during periods of high solar activity, and particularly during magnetic storms (Section 3.2.4).

Because of atmospheric variations, all three co-ordinates displayed on a hand-held GPS will usually vary over a range of several metres within a period of a few minutes, and by several tens of metres over longer time intervals. Despite this, it is now feasible to use a hand-held GPS for surveys with inter-station separations of 100 m or even less because GPS errors, even if significant fractions of station spacing, are not, as are so many other errors, cumulative. Moreover, rapid movement from station to station is, in effect, a primitive form of DGPS, and if fixes at adjacent stations are taken within a few minutes of each other, the error in determining the intervening distance will be of the order of 5 metres or less. (In theory, this will not work, because corrections for transmission path variations should be made individually for each individual satellite used, and this cannot be done with the hand-held instruments currently available. However, if distances and time intervals between readings are both small, it is likely that the same satellite constellation will have been used for all estimates and that the atmospheric changes will also be small.)

1.5.2 Elevations from hand-held GPS receivers

In some geophysical work, errors of the order of 10 metres may be acceptable for horizontal co-ordinates but not for elevations, and DGPS is then still needed. There is a further complication with 'raw' GPS elevations, since these are referenced to an ellipsoid. A national elevation datum is, however, almost always based on the local position of the *geoid* via the mean sea level at some selected port. Differences of several tens of metres between geoid and ellipsoid are common, and the source of frequent complaints from users that their instruments never show zero at sea level! In extreme cases, the difference may exceed 100 m.

Most hand-held instruments give reasonable positional fixes using three satellites but need four to even attempt an elevation. This is because the unknown quantities at each fix include the value of the offset between the instrument's internal clock and the synchronized clocks of the satellite

Figure 1.15 *Garmin 12 hand-held GPS, showing 'navigation' window, which gives position (in UK National Grid co-ordinates in this instance), altitude to the foot or metre, time and (for use in continuous tracking mode) track orientation and speed. The inset shows the 'satellite' window. Satellites potentially available are shown in the main display. Signal strengths are indicated by black columns but no indication is given as to which four are actually being used to calculate position. Satellites not acquired (05 and 30) are highlighted. Note that the 2D/3D NAV indicator is on this display and that there is no warning on the navigation display when only 2D navigation is being achieved (with only three satellites) and the elevation estimate is therefore not usable.*

constellation. Four unknowns require four measurements. Unfortunately, in some cases the information as to whether ‘3D navigation’ is being achieved is not included on the display that shows the co-ordinates (e.g. Figure 1.15), and the only indication that the fourth satellite has been ‘lost’ may be a suspicious lack of variation in the elevation reading.