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INTRODUCTION

1.1 What Geophysics Measures

Applied or exploration geophysics can be defined as mapping the subsurface through the remote measurement of its physical properties. The discipline dates back to ancient times but only since the advent of modern-day instrumentation has its use become widespread. The development of geophysical techniques and equipment during the early to middle parts of the twentieth century was driven by oil and mineral exploration, for targets that could be several kilometres deep. Many of the instruments used today in archaeological, environmental and engineering surveys owe their development to this kind of geophysics, but have been adapted to investigations of the near-surface, in the range of 0.5–100 m.

The success of any geophysical method relies on there being a measurable contrast between the physical properties of the target and the surrounding medium. The properties utilised are, typically, density, elasticity, magnetic susceptibility, electrical conductivity and radioactivity (Table 1.1). Whether a physical contrast is in practice measurable is inextricably linked to the physics of the problem, the design of the geophysical survey and the selection of suitable equipment. Not all equipment is fit for purpose. Often a combination of methods provides the best means of solving a complex problem, and sometimes a target that does not provide a measurable physical contrast can be detected indirectly by its association with conditions or materials that do. One of the aims of this handbook is to give the field observer an appreciation of the notional detectability of targets and the influence of burial setting, survey design, equipment selection and operating procedures on actual detectability.

1.2 Fields

Although there are many different types of geophysical measurement, small-scale surveys all tend to be rather similar 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,

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Field Geophysics, Fourth Edition. John Milsom and Asger Eriksen.

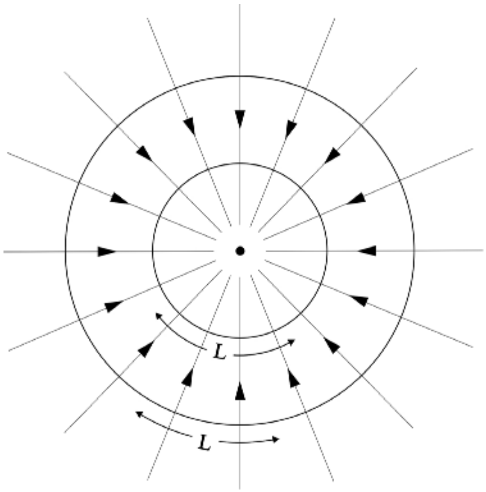

Figure 1.1 *Lines of force from an infinite line source (viewed end on). The distance between the lines increases linearly with distance from the source so that an arc of the inner circle of length L is cut by four lines but an arc of the same length on the outer circle, with double the radius, is cut by only two.*

magnetic and electromagnetic (EM) 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 nearly always used to identify readings made *in* the field, i.e. not at a base station.

Physical fields can be illustrated by lines of force that show the field direction at any point (Figure 1.1). 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.

In Table 1.1 there is a broad division into *passive* and *active* methods. Passive methods use naturally occurring fields (such as the Earth's magnetic field), over which the observer has no control, and detect variations caused by geology or man-made objects. Interpretation is usually non-unique, relying a great deal on the experience of the interpreter. Active methods involve generating signals in order to induce a measurable response associated with

Table 1.1 *Common geophysical techniques*

Technique	Passive/ active	Physical property utilised	Source/signal
Magnetics	Passive	Magnetic susceptibility/ remanence	Earth's magnetic field
Gravity	Passive	Density	Earth's gravitational field
Continuous Wave and Time-Domain Electromagnetics (EM)	Active/ passive	Electrical conductivity/ resistivity	Hz/kHz band electromagnetic waves
Resistivity Imaging/ Sounding	Active	Electrical resistivity	DC electric current
Induced Polarisation	Active	Electrical resistivity/ complex resistivity and chargeability	Pulsed electric current
Self potential (SP)	Passive	Redox and electrokinetic	Redox, streaming and diffusion potentials
Seismic Refraction and Reflection/ Sonic	Active/ passive	Density/elasticity	Explosives, weight drops, vibrations, earthquakes, sonic transducers
Radiometrics	Active/ passive	Radioactivity	Natural or artificial radioactive sources
Ground Penetrating Radar (GPR)	Active	Dielectric properties (permittivity)	Pulsed or stepped frequency microwave EM (50–2000 MHz)
Wireline Logging	Active/ passive	Various	Various

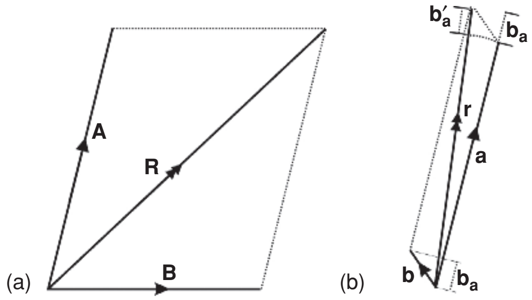

Figure 1.2 *Vector addition by the parallelogram rule. Fields in (a) that are represented in magnitude and direction by the vectors* ***A*** *and* ***B*** *combine to give the resultant* ***R****. In (b), the resultant* ***r*** *of the large field* ***a*** *and the small field* ***b*** *is approximately equal in length to the sum of* ***a*** *and the component* $\boldsymbol{b}_a$ *of* ***b*** *in the direction of* ***a****. The angular difference in direction between* ***a*** *and* ***r*** *is small and therefore the component* $\boldsymbol{b}'_a$ *in the direction of* ***r*** *is almost identical to* $\boldsymbol{b}_a$*.*

a target. The observer can control the level of energy input to the ground and also measure variations in energy transmissibility over distance and time. Interpretation of this type of data can be more quantitative. Depth discrimination is often better than with passive methods, but ease of interpretation is not guaranteed.

1.2.1 Vector addition

When combining fields from different sources, vector addition (Figure 1.2) must be used. 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 of the anomaly in that direction will be measured (Figure 1.2b). The slight difference in direction between the resultant and the background or primary field is usually ignored in such cases.

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 measured by taking all measurements in a single direction and assuming that the component of the background or primary field in that direction is constant over the survey area. Measurements of vertical rather than total field 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 magnetisation in another, or even in itself (*demagnetisation effect*), and the interactions between fields, conductors and currents in electrical and electromagnetic surveys can be very complicated.

1.2.2 The inverse-square law

An 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, and the fact that, in principle, their strength varies with the permeability of the medium is irrelevant in most geophysical work, where measurements are made in either air or water. More important is the fact, which significantly modifies the simple inverse-square law decrease in field strength, that magnetic sources are essentially bipolar (Section 1.2.5).

Electric current flowing from an isolated point-electrode embedded in a continuous homogeneous ground provides a physical illustration of the significance of the inverse-square law. All of the current radiating from 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.

One problem inherent in the inverse-square law control of so many of the fields important in geophysics is *ambiguity*, i.e. the fact that a set of measurements made over a single surface can, in principle, be produced by an infinite number of possible source distributions. Most of these will be geologically impossible, but enough usually remain to render non-geophysical information essential to most interpretations. Figure 1.3 shows two spherical bodies, each with its centre at 5.5 m depth. One, an air void, has a radius of 2.25 m and zero density, whereas the other, a zone of weathered chalk, has a radius of 5 m and a density of $1.9\,\mathrm{Mg\,m^{-3}}$. The surrounding rock is

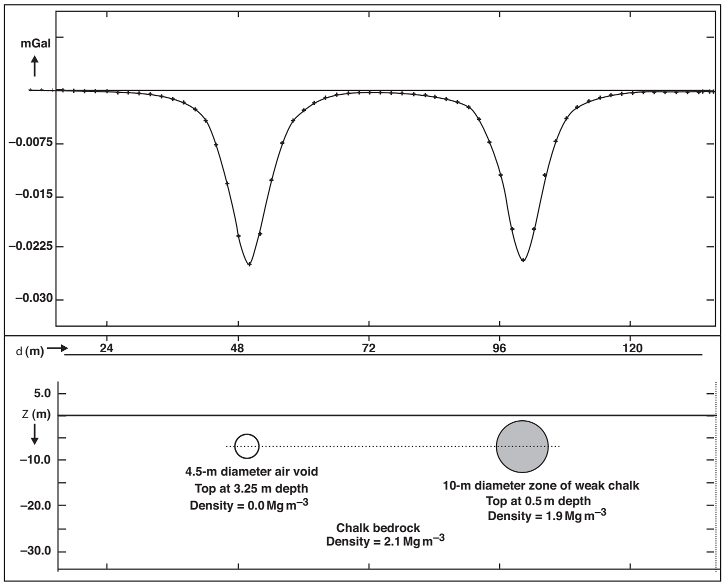

Figure 1.3 *Ambiguity in potential field interpretation. The two very different sources produce almost identical gravity anomalies.*

modelled with the density of 2.1 Mg m^{-3} typical of more competent chalk. The gravitational attraction of each sphere can be calculated assuming the mass deficit is concentrated at its centre. The two anomalies are almost identical, and a follow-on intrusive investigation of each, or a survey using a corroborative geophysical method such as electrical resistivity tomography (Section 6.5) would be required to resolve the ambiguity. Even non-identical anomalies may, of course, differ by amounts so small that they cannot be distinguished in field data.

Ambiguity worries interpreters more than it does the observers in the field, but its existence does emphasise the importance of those observers including in their field notes anything that might possibly contribute to a better understanding of the data that they collect.

1.2.3 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

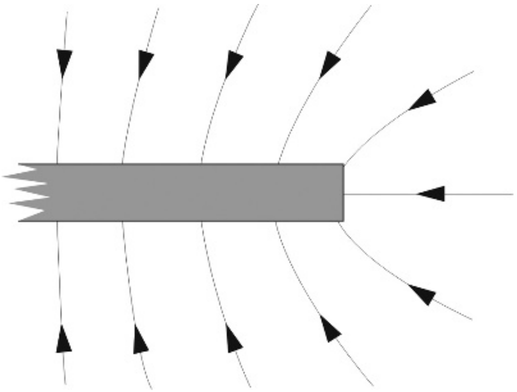

Figure 1.4 *Lines of force from a semi-infinite slab. The lines diverge appreciably only near the edge of the slab, implying that elsewhere the field strength will decrease negligibly with distance.*

termed *two-dimensional (2D)* and are often used in computer modelling to approximate bodies of large strike extent. If the source 'point' in Figure 1.1 represents an infinite line-source seen end-on rather than an actual point, the area of the enclosing (cylindrical) surface is proportional to its radius. The argument applied in the previous section to a point source then leads to the conclusion that the field strength for a line-source will be inversely proportional to distance and not to its square. It follows that, in 2D situations, lines of force drawn on pieces of paper can indicate field intensity (by their separation) as well as direction.

1.2.4 One-dimensional sources

The lines of force or radiation intensity from a source consisting of a homogeneous layer of constant thickness diverge only near its edges (Figure 1.4). The *Bouguer plate* of gravity reductions (Section 2.5.1) and the radioactive source with *2π geometry* (Section 4.3.4) 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.

1.2.5 Dipoles

A dipole consists of equal-strength positive and negative point sources a very small distance apart. Its *moment* is equal to the pole strength multiplied

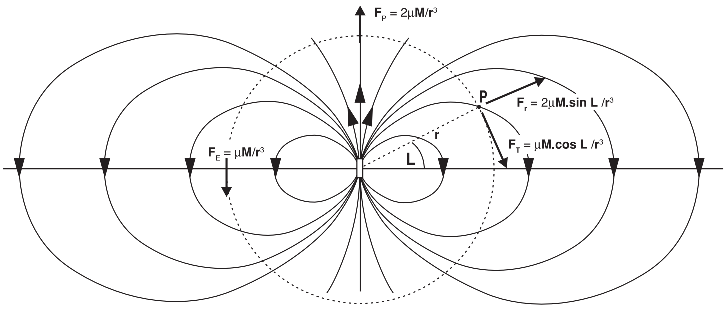

Figure 1.5 *The dipole field. The plane through the dipole at right angles to its axis is known as the equatorial plane, and the angle,* **L***, between this plane and the line joining the centre of the dipole to any point P is sometimes referred to as the latitude of P. The fields shown, at distances r from the dipole centre, are for a dipole with strength (moment)* **M** *(see Section 3.1.1). The values for the radial and tangential fields at P follow from the fact that* **M** *is a vector and can therefore be resolved according to the parallelogram law. The symbol μ is used for the proportionality constant where magnetic fields are concerned (Chapter 3).*

by the separation distance. Field strength decreases as the inverse cube of distance, and both strength and direction change with 'latitude' (Figure 1.5). The intensity of the field at a point on a dipole 'equator' is only half the intensity at a point the same distance away on the dipole axis, and in the opposite direction.

Magnetisation is fundamentally dipolar, and electric currents circulating in small loops are dipolar sources of magnetic field. Many radar antennas are dipolar, and in some electrical surveys the electrodes are set out in approximately dipole pairs.

1.2.6 Exponential decay

Radioactive particle fluxes and seismic and electromagnetic waves are subject to absorption as well as geometrical attenuation, and the energy crossing closed surfaces is less than the energy emitted by the sources they enclose. In homogeneous media, the percentage loss experienced by a plane wave 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 1.6), governed by a *decay constant*, determines the rate of loss of mass by a radioactive substance.

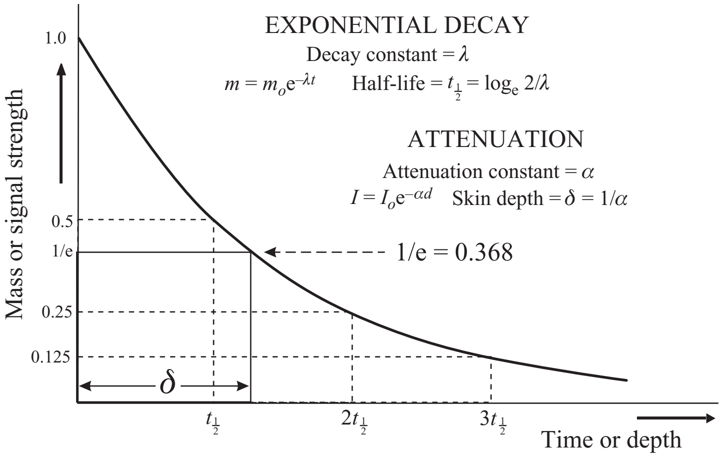

Figure 1.6 *The exponential law, illustrating the parameters used to characterise radioactive decay and radio wave attenuation.*

Attenuation rates are alternatively characterised 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. Radioactive 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.

1.3 Geophysical Survey Design

1.3.1 Will geophysics work?

Geophysical techniques cannot be applied indiscriminately. Knowledge of the material properties likely to be associated with a target (and its burial setting) is essential to choosing the correct method(s) and interpreting the results obtained.

Armed with such knowledge, the geophysicist can assess feasibility and, where possible, select a geophysical method to meet the survey objectives. Table 1.2 lists some of the more important physical properties, for some of the commoner rocks and minerals. Inevitably, the values given are no more than broad generalisations, but the table does at least indicate some of the circumstances in which large contrasts in physical properties might be expected, or at least be hoped for.

Table 1.2 *Important physical properties of common rocks and ore minerals*

Material	Density Mg m^{-3}	Susceptibility SI × 10^6	Resistivity Ohm-m	Conductivity mS m^{-1}
Air	0	0	8	0
Ice	0.9	−9	100 000–8	0–0.01
Fresh water	1	0	1 000 000	0.001
Seawater	1.03	0	0.2	5000
Topsoil	1.2–1.8	0.1–10	50–100	10–20
Coal	1.2–1.5	0–1000	500–2000	2–0.5
Dry sand	1.4–1.65	30–1000	1000–5000	1–0.02
Wet sand	1.95–2.05	30–1000	500–5000	0.2–2
Gravel	1.5–1.8	20–5000	100–1000	1–10
Clay	1.5–2.2	10–500	1–100	10–1000
Weathered bedrock	1.8–2.2	10–10 000	100–1000	1–10
Salt	2.1–2.4	−10	10–10 000 000	0.01–1
Shale	2.1–2.7	0–500	10–1000	1–100
Siltstone	2.1–2.6	10–1000	10–10 000	0.1–100
Sandstone	2.15–2.65	20–3000	200–8000	0.125–5
Chalk	1.9–2.1	0–1000	50–200	5–20
Limestone	2.6–2.7	10–1000	500–10 000	0.1–2
Slate	2.6–2.8	0–2000	500–500 000	0.002–2
Graphitic schist	2.5–2.7	10–1000	10–500	2–100
Quartzite	2.6–2.7	−15	500–800 000	0.00125–2
Gneiss	2.6–2.9	0–3000	100–1 000 000	0.001–10
Greenstone	2.7–3.1	500–10 000	500–200 000	0.005–2
Serpentinite	2.5–2.6	2000–100 000	10–10 000	0.1–100
Granulite	2.7–2.9	100–5000	500–1 000 000	0.001–2
Granite	2.5–2.7	20–5000	200–1 000 000	0.001–5
Rhyolite	2.5–2.7	100–5000	1000–1 000 000	0.001–1
Basalt	2.7–3.1	500–100 000	200–100 000	0.01–5
Dolerite	2.8–3.1	500–100 000	100–100 000	0.01–10
Gabbro	2.7–3.3	100–10 000	1000–1 000 000	0.001–1
Peridotite	3.1–3.4	10–10 000	100–100 000	0.01–10
Pyrite	4.9–5.0	100–5000	0.01–100	10–1 000 000
Pyrrhotite	4.4–4.7	1000–50 000	0.001–0.01	1 000 000–10 000 000
Sphalerite	3.8–4.2	10–100	1000–1 000 000	0.001–1
Galena	7.3–7.7	10–500	0.001–100	10–10 000 000
Chalcopyrite	4.1–4.3	100–5000	0.005–0.1	10 000–200 000
Chromite	4.5–4.7	750–50 000	0.1–1000	1–10 000
Hematite	5.0–5.1	100–1000	0.01–1 000 000	0.001–100 000
Magnetite	5.1–5.3	10 000–10 000 000	0.01–1000	0.001–1
Cassiterite	7.0–7.2	10–500	0.001–10 000	0.1–10 000 000

The design and implementation of a geophysical survey requires careful consideration of the following main factors:

(a) *Target discrimination*
The nature and degree of the contrast in physical properties between a target and its surroundings is of primary importance in the feasibility assessment and choice of techniques. However, information may be limited or non-existent, and in these cases the geophysicist should recommend a trial survey or the application of multiple techniques. Trials are recommended wherever the assumptions made in designing the survey are suspect. Usually a day is all that is required to determine whether the chosen methods can detect the presence of a target in actual field conditions. This is an often neglected stage in the execution of a geophysical survey but is one that could save much geophysicist's pride and client's money were it more routinely used.

Once it has been decided, on the basis of observation, modelling and/or experience, what the geophysical response of a buried target is likely to be, the sensitivity of the equipment and the distribution of the survey stations needed to meet the survey objectives can be specified.

(b) *Detection distance*
In addition to the composition of the target and its surroundings, geophysical methods are sensitive to the relationship between target size and detection distance. In general, the greater the depth of the target, the larger its volume and/or cross-sectional area must be for it to be detectable.

(c) *Survey resolution*
The choice of sampling interval (frequency or spacing of sampling points) is critical to the success of a survey and its cost-effectiveness. The appropriate interval is dictated by the geophysical 'footprint' of the target, which may be tens of centimetres for small-diameter shallow pipes, a few metres for narrow fault zones, and kilometres for ore bodies at depth. An anomaly must be adequately sampled to meet the survey objectives. Although it is almost equally important that resources are not wasted in collecting more data than are required, it has to be remembered that under-sampling can produce completely fictitious anomalies (Figure 1.7).

In some cases, particularly on brownfield sites, surface obstructions can prevent the collection of regularly spaced data. The obstructions may be removable, but unless their impact on the survey outcome is fully understood by the field observer, they may not be dealt with at the appropriate time.

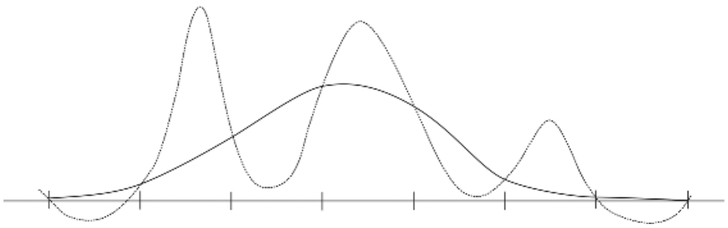

Figure 1.7 *Aliasing. The dashed curve shows a magnetic profile as it should have been recorded, the solid line shows the spurious anomaly that would be deduced by using only data from the widely spaced reading points indicated by vertical lines on the distance axis. Aliasing can occur in time as well as in space, if time-varying signals are sampled too infrequently.*

(d) *Site conditions*
The suitability of a site for collecting good quality geophysical data is often overlooked in survey design. The issues affecting data quality that could be of concern are often specific to the method or methods being proposed. For example, signal degradation may occur or geophysical 'noise' may be introduced in electromagnetic and magnetic surveys by the presence of surface metallic structures and overhead power lines. In microgravity or seismic surveys, noise may result from traffic movements or wind and waves. If the noise exceeds the amplitude of the anomaly due to the target and cannot be successfully removed, the target will not be detectable. The best way to assess the likely influence of site conditions is to visit the site at the design stage and/or carry out a trial survey.

Field observers should be fully briefed on the objectives of the survey and mindful of the design aspects, so that departures of the field conditions from any assumptions made can be reported in good time, allowing the design to be modified where possible. They should immediately report any unexpected conditions, and any geological information provided by drillers to which the geophysicist who designed the survey may not have been privy. They may also obtain useful information relating to previous land-use in conversations with the client or casual passers-by, and this also should be passed on.

1.3.2 Preparing for a survey

The design of a regional or even a local geophysical survey can be greatly assisted by using the geographic data now freely available on the internet.

Google Earth is familiar not only to geophysicists but to almost everyone who has internet access. Only freely available satellite imagery and aerial photographs are used, and quality and geo-registration accuracy vary with location. Images can be saved as .jpg files and it is possible, before so doing, to superimpose survey area outlines or survey grids using standard .kml (ASCII) or .kmz (binary) files. Area dimensions can be quickly estimated, and the area to be surveyed (and the parts that may be unsurveyable because of access restrictions) can be discussed and agreed with the client. The images also provide a practical basis for planning access along routes through farmers' fields. 'Forewarned, forearmed; to be prepared is half the victory' [Miguel de Cervantes Saavedra, seventeenth-century Spanish writer].

Internet-available elevation grids are less widely known, but can be equally useful. The Satellite Radar Tracking Mission (SRTM) used a satellite-mounted synthetic aperture radar interferometer to obtain data during a period of 11 days in February 2000. The targeted landmass extended from 56°S to 60°N, and within this region (containing about 80% of the Earth's land surface) elevation estimates were obtained once for at least 99.96%, twice for at least 94.59% and three or more times for about 50%. The data are now available as one-degree square 'tiles', with a 3 arc-second cell-size (equivalent to about 90 m at the Equator) globally (SRTM3) and an optional 1 arc-second (30-m) cell size in the USA (SRTM1). The Version 2 processed data set was replaced in 2009 by an improved (although usually imperceptibly so) Version 2.1.

The SRTM data as distributed suffered from data gaps in areas of steep topographic gradients. It was inevitable that, with a swathe width of about 225 km and a satellite altitude of 233 km, there would be areas that could not be imaged by a side-looking system. These disadvantages have, to a considerable extent, been overcome in the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) data obtained with Japanese instrumentation mounted from December 1999 onwards on a US Terra spacecraft. Coverage was also wider, from 83°S to 83°N. As with SRTM, ASTER data are distributed in one-degree 'tiles' but with a worldwide 1 arc-second (∼ 30-m) cell size. Elevation data are provided in GeoTIFF format, and each data file is accompanied by a quality (QA) file that indicates data reliability, pixel by pixel.

The ASTER instrument operated stereoscopically in the near infra-red, and could therefore be affected by cloud cover. In most cases this problem was solved by the high degree of redundancy (since the mission lasted much longer than the 11 days of SRTM), but in some cases SRTM data have had to be used for infill. In a few areas where SRTM coverage did not exist, 'bad' pixels remain and are flagged by a −9999 value.

The amount of data collected by ASTER is truly enormous, and analysis and verification is a continuing process.

1.3.3 Procedures

All surveys require adherence to some form of procedure, and the field crew should ensure that this is agreed with the geophysicist before commencing fieldwork. Common aspects include, but are not limited to: daily checks on equipment functionality and sensitivity (sometimes with target seeding, depending on the target); survey station layout (to a specified accuracy); survey grid referencing (to previously agreed mapped features); frequency and nature of data quality and repeatability checks; frequency of data archiving; maintenance and format of decipherable field logbooks; and recording of all client communications. Assumption is the mother of all miscommunication between the office and the field, and a formal record of the agreed procedures is worth its weight in gold.

1.3.4 Metadata

Automation in geophysical work proceeds apace, and is giving increased importance to a distinction that, while always present, was sometimes not even recognised when all information was stored in field notebooks. These notebooks contained not only the numerical values displayed on whatever instruments were being used, but also positional and logistical data and other vital information, such as the observer's name. The term *metadata* is now widely used for this largely non-numeric information. Modern data loggers vary widely in the extent to which metadata can be entered into them, but none, so far, have reached a level of sophistication that would allow notebooks to be dispensed with altogether.

1.4 Geophysical Fieldwork

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

1.4.1 Choosing geophysical instruments

It seems that few instrument designers have ever tried to use 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 50 years, design features have been introduced during the same period, for no obvious reasons, that have actually made fieldwork more difficult. The foldable 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 that are easy to replace or will they be impossible to find outside major cities? If rechargeable batteries are used, how heavy are they, and will they be acceptable for airline transportation? In either case, how long will they keep the instruments working at the temperatures expected in the field? Battery life is reduced in cold climates, and the reduction can be dramatic if the battery is used to keep the instrument at a constant temperature, since not only is the available power reduced but the demands made are increased.

Data displays: Are these clearly legible under all circumstances? A torch is needed to read some displays in poor light, and others are almost invisible in bright sunlight. Large displays are needed if continuous traces or profiles are to be shown, but can exhaust batteries 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 or are abraded?

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 actual 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 operate 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 magnetometer pole, made up of sections that screwed together and ended in a spike that could be stuck into soft ground, has 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 water will collect and then inevitably seep inside?

Automation: Computer control has been introduced into almost all the instruments in current production. 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 usually 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 in extreme cases may demand to know the distance to the next station and even to the next line!

The computer revolution has produced real advances in field geophysics, but has its drawbacks. Most notably, the ability to store data digitally within data loggers has discouraged the making of notes on field conditions where these, however important, do not fall within a restricted range of options. This problem is further discussed in Section 1.7.

1.4.2 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.

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 such piles in opposite directions; that is, 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 that are often features of neat and tidy coils and that 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.

Cable piles can be made portable by dumping 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 a cable is being 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 garden-centre or even home-made versions.

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

1.4.3 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, which increases the wear on the contacts in socket plugs, 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, cables are flexed repeatedly just beyond the clamps, and wires may break within their insulated sleeves 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 minimised 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 special 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.

Figure 1.8 *The geophysical cape in action. Electronics and observer are both dry, with only the sensor bottle exposed to the elements. The observer can retreat still further, to view the display.*

1.4.4 Geophysics in the rain

Geophysicists huddled over their instruments are sitting targets for rain, hail, snow and dust, as well as mosquitoes, snakes and dogs. Their most useful piece of field clothing is often a large waterproof cape, which they can not only wrap around themselves but into which they can retreat, along with their instruments, to continue work (Figure 1.8).

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, field crews should be plentifully supplied with plastic bags and sheeting to protect instruments, and paper towels for 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 amounts of moisture but cannot cope with large volumes, and a portable hair-drier held at the base camp may be invaluable.

1.4.5 A geophysical toolkit

Regardless of the specific type of geophysical instruments involved, 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 12-V 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/flashlight (either a type that will stand unsupported and double as a table lamp or a 'head torch')
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 important, and a legal necessity in many countries.

1.5 Geophysical Data

Geophysical readings may be of true *point data* but may also be obtained using *arrays* where sources are separated from detectors and where values are determined *between* rather than *at* points. In most such cases, readings will be affected by array orientation. Precise field notes are always important but especially if arrays are involved, since reading points must then be defined and array orientations must be recorded.

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

1.5.1 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 $3^1/_4$, $3^1/_2$ and $3^3/_4$ 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 that may be needed, with digital field systems or in subsequent processing, to stand for N or E. It is good practice to define 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 directions.

Stations scattered randomly through an area are best numbered sequentially, as read. Positions can be recorded in the field by pricking through the field maps or air-photos and labelling the reverse sides. Estimating coordinates from maps in the field may seem desirable but mistakes are easily made and valuable time is lost. Station coordinates are now often obtained from GPS receivers (see Section 15.2), but differential or RTK (*real-time kinetic*) GPS may be needed to provide enough accuracy in 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.

1.5.2 Recording results

Geophysical results are primarily numerical and must be recorded even more carefully than the 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 also 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. They may, under such conditions, delete correct results and replace them with incorrect ones, and data recorded 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 corrected 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 minimised. 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 with the originals. This, of course, applies equally to data stored in data loggers incorporated in, or linked to, field instruments. Such data should be downloaded, checked and backed-up each evening.

Digital data loggers can greatly simplify field operations but are often poorly adapted to storing non-numeric metadata. This design feature ignores the fact that observers are uniquely placed to note and comment on a multitude of topographic, geological, man-made (*cultural*) and climatic factors that may affect the geophysical results. If they fail to do so, the data they have gathered may be interpreted incorrectly. If data loggers are not being used, comments should normally be recorded in the 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. Field observers also have a responsibility to pass on to their geological or geophysical colleagues information of interest about places that only they may visit. Where these would be useful, they should be prepared to record dips and strikes, and perhaps to return with rock samples.

1.5.3 Accuracy, sensitivity, precision

Accuracy must be distinguished from sensitivity. A modern gravity meter, for example, may be sensitive to field changes of 1 microGal 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 (see Example 1.1). Not only does superfluous precision waste time but false conclusions may be drawn from a high implied accuracy.

Example 1.1

Gravity reading = 858.3 scale units
Calibration constant = 0.10245 mGal per scale division (see Section 2.2.6)
Converted reading = 87.932835 mGal
But reading accuracy is only 0.01 mGal (approximately), and therefore:
Converted reading = 87.93 mGal

(Note that five decimal place precision is needed in the calibration constant, because 858.3 multiplied by 0.00001 is equal to almost 0.01 mGal)

Geophysical measurements can sometimes be made with more accuracy than the interpreters need or can use. However, the highest possible accuracy should always be sought, as later advances may allow the data to be analysed more effectively.

1.5.4 Drift

A geophysical instrument will usually not record the same result if read repeatedly at the same place. *Drift* may be due to changes in background field but can also be caused by changes in the instrument itself. Drift correction is often the essential first stage in data analysis, and is usually based on repeat readings at *base stations* (Section 1.6).

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 1 or 2 hours.

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. Drift calculations should be made whilst the field crew is still in the survey area, so that readings can be repeated if the drift-corrected results appear suspect.

1.5.5 Repeatability

Repeat data are vital for checking whether an instrument is performing to specification. Ideally, a repeat survey line should be completed on every survey grid before moving to the next grid. For linear transects or meandering surveys, a minimum of 5% of repeat data is required. Repeat line-data achieve two things – they confirm that the instrument is responding consistently and they also provide a measure of the positioning accuracy. Where geophysical anomalies are small, it may be prudent to collect more than one repeat line per survey grid, because of low signal-to-noise ratios. In gravity surveys requiring microGal resolution, it may be necessary to reoccupy two or more stations in each loop. Repeatability requirements should be discussed and agreed with the client before a survey begins.

1.5.6 Detection limits

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. Using geophysics to locate a target is in some ways analogous to receiving a mobile phone message. If the ratio of signal to noise is high (good 'reception'), a target may be found at close to the theoretical limits of detection. If the signal is weak it may not be possible to distinguish enough of the 'conversation' to make it understandable, or the 'connection' may be lost completely. 'Made' ground often contains material that interferes with the geophysical signal, so that the signal-to-noise ratio may be low even though the signal is strong. It may then not be possible to distinguish the target.

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.

1.5.7 Variance and standard deviation

The statistics of random noise are important in seismic, ground radar, radiometric and induced polarisation (IP) surveys. Adding together N statistically-long random series, each of average amplitude A, produces a random series with amplitude $A \times \sqrt{N}$. Since N identical signals of average amplitude A treated in this 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 $\sqrt{N}$.

Random variations may have a *normal* or *Gaussian* distribution, producing a bell-shaped probability curve. A normal distribution can be characterised by a *mean* (equal to the sum of all the values divided by the total

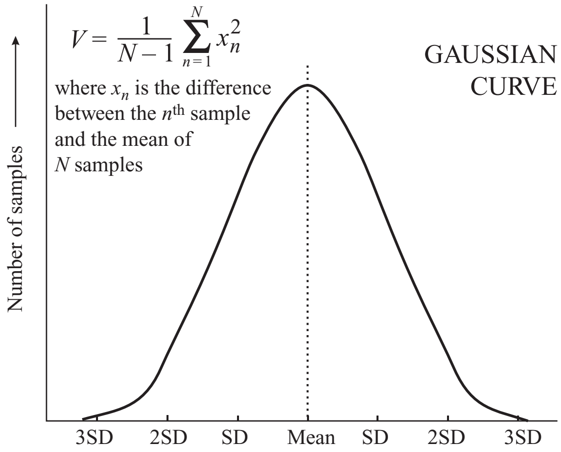

Figure 1.9 *Gaussian distribution. The curve is symmetric, and approximately two-thirds of the area beneath it lies within one standard deviation (SD) of the mean.* V = *variance.*

number of values) and a *variance* (V, defined in Figure 1.9) or its square root, the *standard deviation* (SD). About two-thirds of the readings in a 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. However, it is rare, in many types of geophysical survey, for enough field data to be obtained for statistical methods to be validly applied, and distributions are often assumed to be normal when they cannot be shown to be so.

Gaussian and more sophisticated statistical summaries of data (both background and target-related) are recommended for unexploded ordnance (UXO) surveys, where confidence is essential, to quantify the detection assurance level (the distance from a sensor within which a target of a certain size can be detected with 100% confidence). This measure will vary from site to site, and within a site, depending on the variable composition of made ground or geology, as well as on target size.

1.5.8 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* – that is, on differences from a constant or smoothly varying background. Anomalies take many forms. A massive sulphide deposit containing pyrrhotite would be dense, magnetic and electrically conductive (Table 1.2). Typical anomaly profiles recorded over such a body by various types of geophysical survey are shown in Figure 1.10. 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 'mineralisation' 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 that is not influenced by the anomalous values (Figure 1.11). Computer methods are, however, essential when deriving backgrounds from data gathered over areas rather than along single lines.

The existence of an anomaly indicates a difference between the real world and some simple model, and in gravity work the terms *free-air anomaly*, *Bouguer anomaly* 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 – that is, the area is not anomalous! Use of terms such as Bouguer *gravity* (rather than Bouguer anomaly) avoids this confusion.

1.5.9 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 where geophysical anomalies are concerned the use is imprecise, since an anomaly described as having a single 'wavelength' would be resolved by Fourier analysis into a number of components with 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 1.10a). 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.

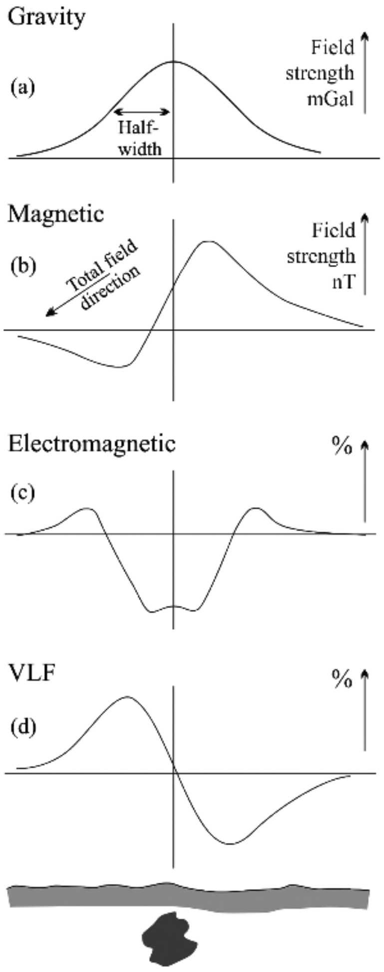

Figure 1.10 Geophysical profiles across a pyrrhotite-bearing sulphide mass. The amplitude of the gravity anomaly (a) might be a few tenths of a milliGal, and of the magnetic anomaly (b) a few hundred nanotesla (nT). The electromagnetic anomalies are for a two-coil co-planar system (c) and a dip-angle system (d). Neither of these is likely to have an amplitude of more than about 20%.

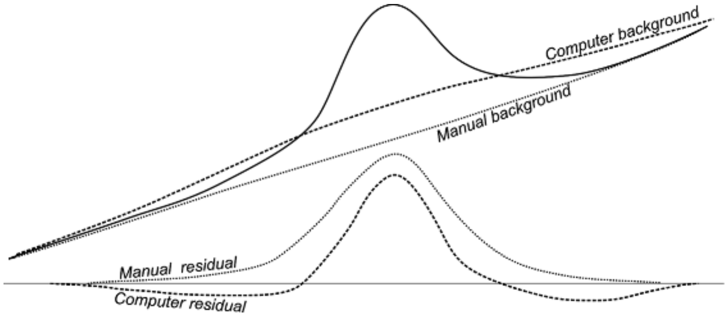

Figure 1.11 *Computer and manual residuals. The background field drawn by eye recognises the separation between regional and local anomaly, and the corresponding residual anomaly is probably a good approximation to the actual effect of the local source. The computer-drawn background field is biased by the presence of the local anomaly, and the corresponding residual anomaly is therefore flanked by troughs.*

1.5.10 Presentation of results

The results of surveys along traverse lines can be presented in profile form, as in Figure 1.10. 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. Most field crews now carry laptop computers, which can reduce the work involved, and many modern instruments and data loggers will display profiles in real time as work proceeds.

A traverse line plotted 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 man-made features, since correlations with features such as roads and field boundaries are obvious. If profiles along a number of parallel 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 1.5.7).

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 the routine use of laptop computers has vastly reduced the work involved. Information is, however, 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

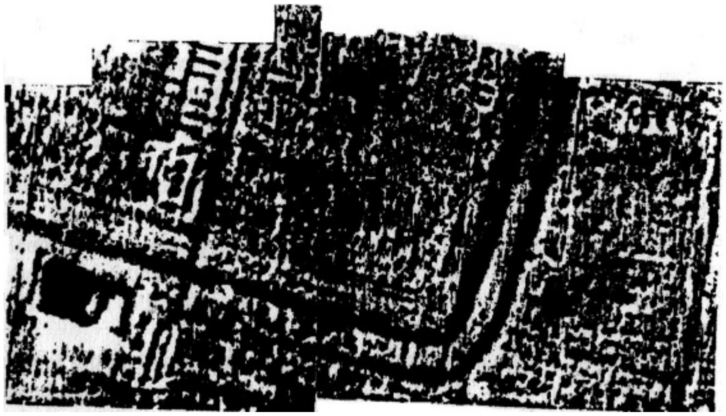

Figure 1.12 *Image-processed magnetic data over an archaeological site. (Reproduced by permission of Professor Irwin Scollar.)*

field quality control. Contoured cross-sections (*pseudo-sections*) are used to display the results of some types of electrical survey.

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 critically important. Noise is filtered by eye, patterns such as those in Figure 1.12 being easily recognised as due to human activity.

It can also be revealing to overlay contoured results on a Google Earth or other image. Many tools are available for doing this, ranging from full Geographic Information Systems (GIS) to simpler packages such as Global Mapper. Some also allow the transparency of overlaid pixel-based images to be adjusted so that features on the ground can be correlated with patterns in the geophysical data. This can be a powerful interpretation tool, provided, of course, that the ground features imaged were actually there at the time of the survey. It is also a valuable way of showing results to clients.

1.6 Bases and Base Networks

Bases or *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.

1.6.1 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 start 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.

1.6.2 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 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 background 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.

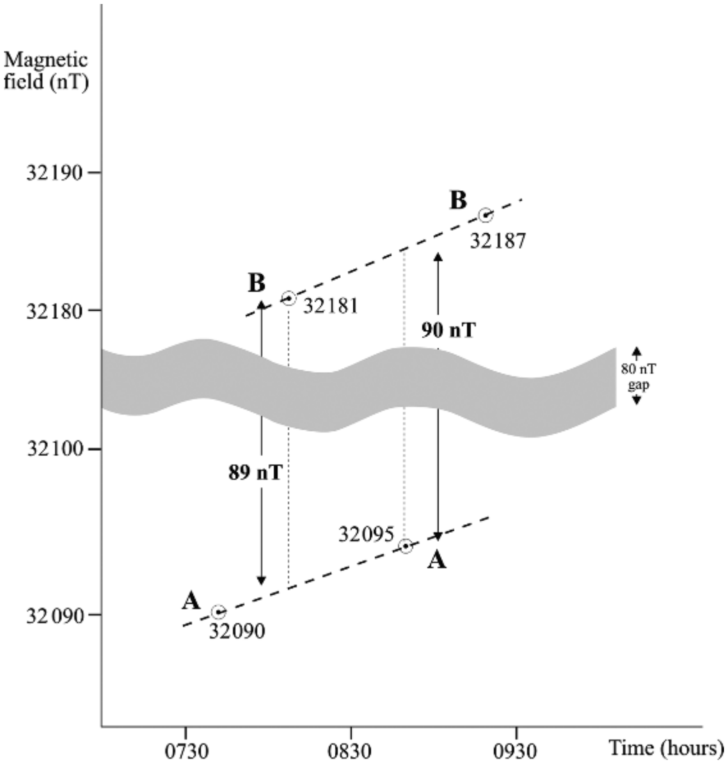

Figure 1.13 ABAB tie between bases in a magnetic survey with a 1-nT instrument. The estimated difference between the two stations would be 89 nT. Note that the plotting scale should be appropriate to instrument sensitivity and that it may be necessary to 'remove' some of the range of the graph to allow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

Differences should be calculated in the field so that any necessary extra links can be added immediately.

1.6.3 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 small. Even so, the final value obtained at the end of an

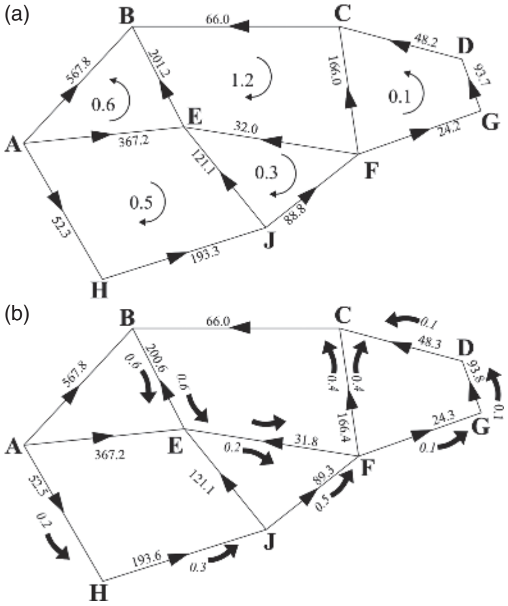

Figure 1.14 *Network adjustment. (a) The 1.2-unit misclosure in loop BCFE suggests a large error in either the 'unsupported' link BC or in BE, the only link shared with another loop with a large misclosure. (b) Adjustments made on the assumption that BC was checked and found to be correct but that no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

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 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.

1.6.4 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 reoccupations. 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 such points that are distinctive because of the presence of man-made or natural features. Written descriptions and sketches are the best way to preserve the information for the future. Sketches, such as those shown in Figure 2.7, are usually better than photographs, because they can emphasise salient points.

Permanence can be a problem, and maintaining gravity bases at international airports is almost impossible because building work is almost always underway (and, these days, because attempting to read a geophysical instrument anywhere near an airport is likely to trigger a security alert). Geodetic survey markers are usually reliable 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.

1.7 Real-Time Profiling

During the past 20 years, automation of the geophysical equipment used 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, 40 years ago, to put a man on the Moon.

1.7.1 Data loggers

The integration of data loggers into geophysical instruments has its drawbacks. At least one manufacturer proudly boasted ‘no notebook’, even though the instrument in question was equipped with only a numerical key pad so that there was no way of entering text comments (*metadata*) into the (more than ample) memory. Other automated instruments have data displays that are so small and so poorly positioned that the possibility that the observer might actually want to look at, and even think about, the observations as they are being collected has clearly not been considered. Unfortunately, pessimism in this respect is often justified, partly because of the speed with which readings, even when essentially 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 at least once every day. 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 attached, are essential rather than optional if instruments are dragged, pushed or carried along a traverse to provide virtually continuous readings. In many cases, 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. Additional keystrokes should be used to ‘mark’ the passing of intermediate survey points on lines more than about 20 m long, but even this can be made unnecessary by integrating a DGPS unit (see Section 15.2) into the system. Many instruments can now record GPS data and can be synchronised using the GPS signal as a common time reference, enabling on-the-move recording to almost 1-metre positional accuracy with relatively cheap systems and without significant loss of data quality (Figure 1.15). Apart from the obvious productivity benefits of lines being traversed more quickly and survey grids being set out in significantly less time, the permanent record of where the instrument has actually measured data is valuable for quality control.

Figure 1.15 *Magnetometer coupled to a differential GPS navigation system for continuous profiling. Unless allowance is made in processing for the offset between the GPS and magnetic sensors, anomaly locations will be incorrectly plotted (photo courtesy of Geometrics).*

Figure 1.16 *Geonics EM-31 mounted on a quad bike. Induced currents will flow in the vehicle as well as in the ground, but should be reasonably constant.*

1.7.2 Vehicle-mounted systems

The increasing use of vehicle-mounted systems in medium- to large-scale geophysical surveys is a particularly welcome trend for those who (like the authors) have been worn down by a lifetime of walking lines carrying instruments. The system shown in Figure 1.16 is a good example of life being made very much easier. It was used to record ground conductivity data to delineate a fault, using a Geonics EM31-Mk2 and a DGPS system with EGNOS capability (see Section 15.2) to 2 m spatial accuracy, in less than one-third of the time it would have taken on foot.

Most continuously recording geophysical instruments can be mounted in this way, achieving significant cost benefits in open areas more than 5 hectares in area, if these are to be covered by lines more than 2 m apart. The agricultural quad-bike is the vehicle of choice. The main precaution required is regular checking of satellite coverage, and care must also be taken to travel at speeds compatible with the station interval needed to map the target. It is all too tempting to try to squeeze in a few extra lines by opening the throttle.

Figure 1.17 *Multiple systems mounted on a purpose-built wooden sledge.*

1.7.3 Towed systems

Putting a sensor on a survey vehicle is undesirable if the vehicle is likely to be a source of noise. It may also be difficult to mount all the equipment needed for a multi-system survey on the vehicle and still leave room for the driver. Towing the instruments behind the vehicle on a purpose-built sledge then becomes a better option. The towed system in Figure 1.17 was used to record combined ground conductivity, natural gamma and multiple total field magnetometer data to simultaneously map shallow geological deposits, cross-cutting pipelines, archaeological features and buried pits along a proposed linear route. A DGPS system with EGNOS availability (see Section 15.2) was used to record locations to approximately 2-m spatial accuracy.

Multi-instrument platforms in their most advanced form have been developed in the USA to improve the efficiency of scanning firing ranges and battlefields with multiple magnetometers and time domain EM systems synchronised so that they do not affect each other. The systems utilise not only real-time GPS control but are integrated with inertial navigation units to provide accurate dead reckoning navigation in the event of poor GPS signal. These platforms offer huge cost savings compared with separate surveys or surveys on foot. The cost of negotiating land access can also be significantly reduced, because only a single visit is needed.

Designing towed systems can be challenging. Some signal sources will interfere with unrelated sensors if located too close to them without transmission and data-capture synchronisation, so the sensor layout must be carefully planned. Systems such as that shown in Figure 1.17 work well in reasonably flat terrain and in dry conditions. Add topography and wet weather, and the need to monitor the state of multiple instruments whilst tracking a survey grid barely visible on the screen of a tablet PC, and the days of trudging along lines on foot can seem like a lost paradise.

Handling the increase in data volumes and ensuring the accurate synchronisation of multiple datasets is also non-trivial, requiring a rigid set of procedures involving daily tests of repeatability and sensitivity and of the influence of the towing vehicle. It will also, inevitably, be necessary to deal with dropouts in one or more data channels. The process is not for the faint-hearted, and commercial surveys demand previous experience in running multi-instrument platforms and careful and detailed planning.

1.7.4 Errors in continuously recorded data

One consequence of semi-continuous operation has been the appearance in ground surveys of the sorts of errors that were once common in airborne surveys but 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 carried system shown in Figure 1.15, 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 keystrokes on a data logger. If the key is depressed when the operator, 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 a grid are traversed in opposite directions, a *herringbone* pattern (Figure 1.18) can 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.

False anomalies can 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 1.15 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, as minor peaks and troughs on adjacent lines are linked to each other during contouring. On slopes there

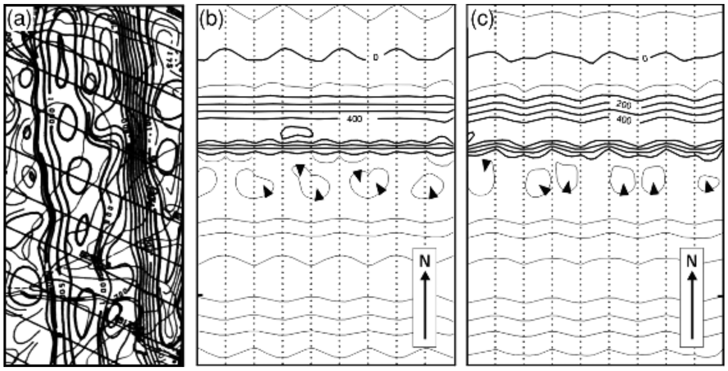

Figure 1.18 *Distortion in automated contouring of linear anomalies. (a) Introduction of closures in the peak of a linear aeromagnetic anomaly caused by the contouring program seeking (as most do) to equalise gradients in all directions. A similar effect can be seen in the 'bubbling' of the very closely spaced contours on the south side of the anomaly in (b). In neither case are the features required by the actual data, which exist only along the traverse lines indicated by lines in (a) and by discrete points in (b). (b) 'Herringbone' pattern due to a consistent difference in background levels on lines measured in opposite directions (see discussion in text). The effect is barely visible on the large main anomaly (thick contours at 100-nT intervals) but very obvious in the low-gradient areas where contours are at 10-nT intervals. (c) 'Herringbone' pattern due to parallax error. In this case there is a consistent offset between contour 'cuts' along lines recorded in opposite directions, regardless of anomaly magnitude.*

will inevitably be a tendency for a sensor carried in front of the observer to be closer to the ground when going uphill than when going downhill. How this effect will appear on the final maps will vary with the nature of the terrain, but in an area with constant slope there will be 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 1.18).

Heading errors occurred in airborne (especially aeromagnetic) surveys because the effect of the aircraft on the sensor depended on aircraft orientation. A similar effect can occur in a ground magnetic survey if the observer is carrying any iron or steel material. The induced magnetisation in these objects will vary according to the facing direction, producing effects similar to those described above as being produced by constant slopes.

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 data-logged ground surveys. 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, the most that can be done is to increase the number of ‘marker’ points.