Field Geophysics

THIRD EDITION

John Milsom
University College London

WILEY

Field Geophysics

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PREFACE TO THE FIRST EDITION

The purpose of this book is to help anyone involved in small-scale geophysical surveys. It is not a textbook in the traditional sense, in that it is designed for use in the field and concerns itself with practical matters – with theory taking second place. Where theory determines field practice, it is stated, not developed or justified. For example, no attempt is made to explain why four-electrode resistivity works where two-electrode surveys do not.

The book does not deal with marine, airborne or downhole geophysics, nor with deep seismic reflection work. In part this is dictated by the space available, but also by the fact that such surveys are usually carried out by quite large field crews, at least some of whom, it is to be hoped, are both experienced and willing to spread the benefit of that experience more widely.

Where appropriate, some attention is given to jargon. A field observer needs not only to know what to do but also the right words to use, and right in this context means the words which will be understood by others in the same line of business, if not by the compilers of standard dictionaries.

A words of apology is necessary. The field observer is sometimes referred to as 'he'. This is unfortunately realistic, as 'she' is still all too rare, but is not intended to indicate that 'she' is either unknown or unwelcome in the geophysical world. It is hoped that all geophysical field workers, whether male or female and whether geophysicists, geologists or unspecialized field hands, will find something useful in this book.

Finally, a word of thanks. Paul Hayston of BP Minerals and Tim Langdale-Smith of Terronics read early drafts of the text and made numerous invaluable suggestions. To them, to Janet Baker, who drew many of the sketches, and to the companies which provided data and illustrations, I am extremely grateful.

PREFACE TO THE SECOND EDITION

Since the first edition of this book was published in 1989, there have been some changes in the world of field geophysics, not least in its frequent appearance in television coverage of arthaeological 'digs'. In this work, and in surveys of contaminated ground and landfill sites (the archaeological treasure houses of the future), very large numbers of readings are taken at very small spacings and writing down the results could absorb a major part of the entire time in the field. Automatic data logging has therefore become much more important and is being make ever easier as personal computers become smaller and more powerful. New field techniques have been developed and image processing methods are now routinely used to handle the large volumes of data. Comments made in the first edition on the need to record information about the survey area as well as geophysical data have equal, and perhaps even more, force in these instances, but it is obviously usually not practical or appropriate to make individual notes relating to individual readings.

The increase in the number of geophysical surveys directed at the very shallow subsurface (1–5 m) has also led to the increasing use of noncontacting (electromagnetic) methods of conductivity mapping. Moreover, the increased computing power now at every geophysicist's disposal has introduced inversion methods into the interpretation of conventional direct current resistivity soundings and has required corresponding modifications to field operations. It is hoped that these changes are adequately covered in this new edition. a further development has been the much wider availability of ground penetrating radar systems and a recent and fairly rapid fall in their cost. A chapter has been added to cover this relatively new method.

Much else has remained unchanged, and advances in airborne techniques have actually inhibited research into improving ground-based instrumentation for mineral exploration. Automatic and self-levelling gravity meters are becoming more widely available, but are still fairly uncommon. Magnetometers more sensitive than the conventional proton precession or fluxgate instruments are widely advertised, but in most circumstances provide more precision than can be readily used, except in the measurement of field gradients. VLF methods are enjoying something of a revival in exploration for fracture aquifers in basement rocks, and the importance of ease of use is being recognized by manufacturers. Instruments for induced polarization and time-domain electromagnetic surveys also continue to be improved, but their basic principles remain unchanged. More use is being made of reflected seismic waves, partly because of the formerly undreamed of processing power now available in portable field seismographs, but refraction still dominates seismic studies of the shallow subsurface.

Inevitably, not all the methods currently in use could be covered in the space available. Seismo-electrical methods, in which the source pulses are mechanical and the signal pulses are electrical, are beginning to make their presence felt and may demand a place in textbooks in the future. Few case histories have yet been published. Magnetotelluric methods have a much longer history and continue to be developed, in conjunction with developments in the use of controlled (CSAMT) rather than natural sources, but many general purpose geophysicists will go through their entire careers without being involved in one such survey.

Despite the considerable rewriting, and the slight increase in size (for which I am immensely grateful to the new publishers), the aim of the book remains the same. Like its predecessor it is not a textbook in the conventional sense, but aims to provide practical information and assistance to anyone engaged in small-scale surveys on the ground. In helping me towards this objective, I am grateful particularly to Paul Hayston (RTZ) for introducing me to mineral exploration in a new and exciting area, to Asgeir Eriksen of Geophysical Services International (UK) for keeping me in touch with the realities of engineering and ground-water geophysics, and to my students for reminding me every year of where the worst problems lie. I am also grateful to all those who have given their permission for illustrations to be reproduced (including my daughter, Kate, whose view of field geophysics is shown in Fig. 5.1), and most especially to my wife, Pam, for retyping the original text and for putting up with this all over again.

John Milsom

PREFACE TO THE THIRD EDITION

In the decade and a half since the preparation of the first edition of this handbook there have been few fundamental changes in the methods used in small-scale ground geophysical surveys. There have, however, been radical changes in instrumentation, and far-reaching developments in applications. The use of geophysics in mineral exploration has declined, both in absolute terms (along with the world-wide decline in the mining industry itself), and relative to other uses. What is loosely termed environmental, engineering or industrial geophysics has taken up much of the slack. Sadly, the search for unexploded ordnance (UXO) is also assuming ever-increasing importance as more and more parts of the world become littered with the detritus of military training and military operations (the much more lethal search for landmines which, unlike UXO, are deliberately designed to escape detection, also uses geophysical methods but is emphatically *not* covered in this book). Archaeological usage is also increasing, although still inhibited in many cases by the relatively high cost of the equipment.

In instrumentation, the automation of reading and data storage, which was only just becoming significant in the late 1980s, has proceeded apace. Virtually all the new instruments coming on to the market incorporate data loggers and many include devices (such as automatic levelling) to make operations quicker and easier. This, and the fact that virtually every field crew now goes into the field equipped with at least one laptop PC, has had two main, and contrasting, consequences. On the one hand, the need for specialist skills in the field personnel actually operating the instruments has been reduced, and this is leading to a general decline in the quality of field notes. On the other hand, much more can now be done in the field by way of processing and data display, and even interpretation. The change is exemplified by ground radar units, which provide users with visual (even though distorted) pictures of the subsurface while the survey is actually under way. Interestingly, the trend towards instruments that provide effectively continuous coverage as they are dragged or carried along lines has led to the emergence in ground surveys of errors that have long plagued airborne surveys but have now been largely eliminated there. Comments made in the first edition on the need to record information about the survey area as well as geophysical data have equal, and perhaps even more, force in these instances, but it is obviously usually neither practical nor appropriate to make individual notes relating to individual readings.

The increase in the number of geophysical surveys directed at the very shallow subsurface (1–5 m) has also led to the increasing use of electromagnetic methods of conductivity mapping and the development of non-contacting electrical methods which use capacitative rather than inductive coupling. A chapter section has been added to cover this latter, relatively new, method. Other new sections deal with GPS navigation, which has become immensely more useful to geophysicists since the removal of 'selective availability' and with audio-magnetotellurics (AMT), largely considered in the context of controlled sources (CSAMT) that mimic the natural signals but provide greater consistency.

There has also been a slight change in the notes and bibliography. Providing references to individual papers is a problem in a book of this size, and I have actually reduced the number of such references, confining myself to older papers containing some fundamental discussion, and to papers that are the sources of illustrations used. I have also eliminated the section on manufacturers' literature, not because this literature is any less voluminous or important, but because it is now largely available through the Internet. A number of key URLs are therefore given.

Despite the considerable rewriting, and the slight increase in size (for which I am again immensely grateful to the publishers), the aim of the book remains unchanged. Like its predecessors, it is not a textbook in the conventional sense, but aims to provide practical information and assistance to anyone engaged in small-scale surveys on the ground. In helping me towards achieving this objective, I am grateful particularly to Chris Leech of Geomatrix for involving me in some of his training and demonstration surveys, to Asgeir Eriksen of Geophysical Services International (UK) for keeping me in touch with the realities of engineering and groundwater geophysics, and to my students for incisive and uninhibited criticisms of earlier editions. I am also grateful to all those who have given their permission for illustrations to be reproduced (including my daughter, Kate, whose view of field geophysics is shown in Figure 5.1), and most especially to my wife, Pam, for exhaustive (and exhausting) proofreading and for putting up with this for a third time.

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.

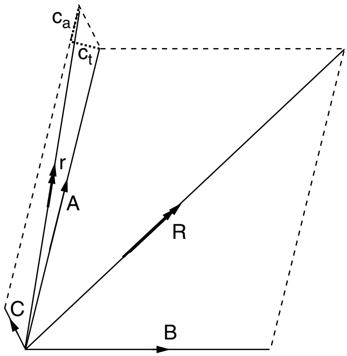

Figure 1.1 *Vector addition by the parallelogram rule. Fields represented in magnitude and direction by the vectors A and B combine to give the resultant R. The resultant* **r** *of A and the smaller field C is approximately equal in length to the sum of A and the component* c_a *of C in the direction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

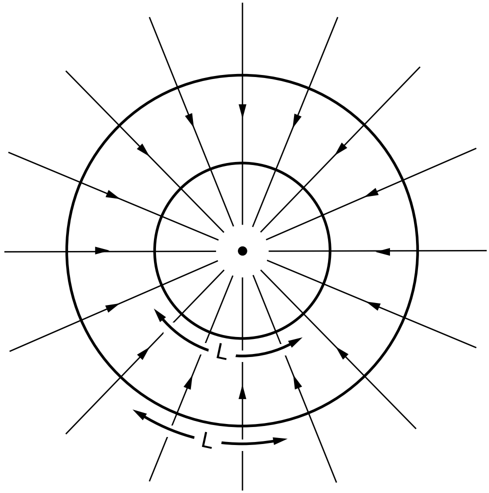

Figure 1.2 *Lines of force from an infinite line source (viewed end on). The distance between the lines increases linearly with distance from the source so that an arc of length L on the inner circle is cut by four lines but an arc of the same length on the outer circle, with double the radius, is cut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

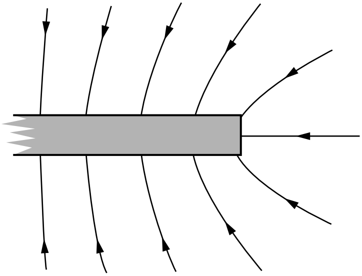

Figure 1.3 *Lines of force from a semi-infinite slab. The lines diverge appreciably only near the edge of the slab, implying that towards the centre of the slab the field strength will decrease negligibly with distance.*

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

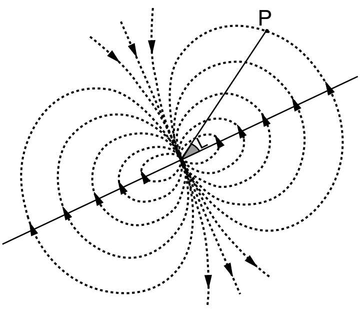

Figure 1.4 *The dipole field. The plane through the dipole at right angles to its axis is known as the equatorial plane, and the angle (L) between this plane and the line joining the centre of the dipole to any point (P) is sometimes referred to as the latitude of P.*

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

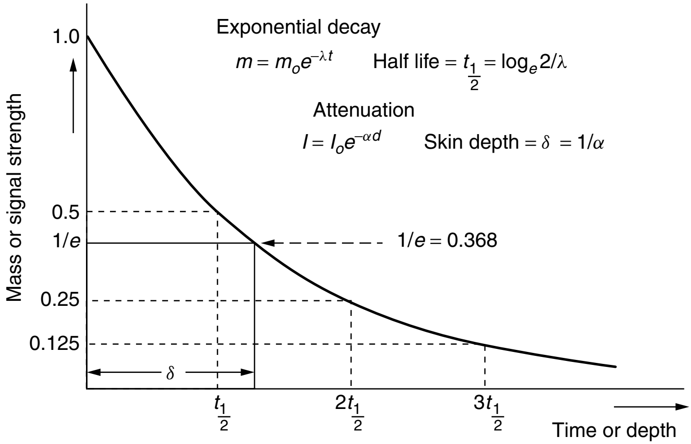

Figure 1.5 *The exponential law, illustrating the parameters used to characterize radioactive decay and radio wave attenuation.*

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