8

ELECTROMAGNETIC METHODS

Electromagnetic (EM) induction, which is a source of noise in resistivity and IP surveys (Chapters 6 and 7), is the basis of a number of geophysical methods. These were originally mainly used in the search for conductive sulphide mineralization but are now being increasingly used for area mapping and depth sounding. Because a small conductive mass within a poorly conductive environment has a greater effect on induction than on 'DC' resistivity, discussions of EM methods tend to focus on conductivity (σ), the reciprocal of resistivity, rather than on resistivity itself. Conductivity is measured in mhos per metre or, more correctly, in siemens per metre ($\mathrm{S\,m^{-1}}$).

There are two limiting situations. In the one, eddy currents are induced in a small conductor embedded in an insulator, producing a discrete anomaly that can be used to obtain information on conductor location and conductivity. In the other, horizontal currents are induced in a horizontally layered medium and their effects at the surface can be interpreted in terms of apparent conductivity. Most real situations involve combinations of layered and discrete conductors, making greater demands on interpreters, and sometimes on field personnel.

Wave effects are important only at frequencies above about 10 kHz, and the methods can otherwise be most easily understood in terms of varying current flow in conductors and varying magnetic fields in space. Where the change in the inducing primary magnetic field is produced by the flow of sinusoidal alternating current in a wire or coil, the method is described as continuous wave (CWEM). Alternatively, transient electromagnetic (TEM) methods may be used, in which the changes are produced by abrupt termination of current flow.

8.1 Two-coil CW Systems

A current-carrying wire is surrounded by circular, concentric lines of magnetic field. Bent into a small loop, the wire produces a magnetic dipole field (Figure 1.4) that can be varied by alternating the current. This varying magnetic field causes currents to flow in nearby conductors (Section 5.3.2).

8.1.1 System descriptions

In CW (and TEM) surveys, sources are (usually) and receivers are (virtually always) wire loops or coils. Small coil sources produce dipole magnetic fields that vary in strength and direction as described in Section 1.1.5. Anomaly amplitudes depend on the coil magnetic moments, which are proportional to the number of turns in the coil, the coil areas and the current circulating. Anomaly shapes depend on system geometry as well as on the nature of the conductor.

Coils are described as horizontal or vertical according to the plane in which the windings lie. 'Horizontal' coils have vertical axes and are alternatively described as *vertical dipoles*. Systems are also characterized by whether the receiver and transmitter coils are *co-planar*, *co-axial* or *orthogonal* (i.e. at right angles to each other), and by whether the coupling between them is a maximum, a minimum or variable (Figure 8.1).

Co-planar and co-axial coils are maximum-coupled since the primary flux from the transmitter acts along the axis of the receiver coil. Maximum-coupled systems are only slightly affected by small relative misalignments but, because a strong in-phase field is detected even in the absence of a conductor, are very sensitive to changes in coil separation. Orthogonal coils are minimum-coupled. The primary field is not detected and small changes in separation have little effect. However, large errors are produced by slight misalignments. In the field it is easier to maintain a required coil separation than a relative orientation, and this is one reason for favouring maximum coupling.

Dip-angle systems, in which the receiver coil is rotated to determine the dip of the resultant field, were once very popular but are now generally limited to the *shoot-back* instruments used in rugged terrain. Shoot-back receiver and transmitter coils are identical and are linked to electronic units that can both transmit and receive. Topographic effects are cancelled by measuring and averaging the receiver coil dip angles with first one and then the other coil held horizontal and used as transmitter.

8.1.2 Slingram

Most ground EM systems use horizontal co-planar coils ('horizontal loops'), usually with a shielded cable carrying a phase-reference signal from transmitter to receiver. The sight of two operators, loaded with bulky apparatus and linked by an umbilical cord, struggling across rough ground and through thick scrub, has provided light entertainment on many surveys. Very sensibly, some instruments allow the reference cable to be also used for voice communication. Fortunately, memory units have not (yet) been added to record the conversations.

The Swedish term *Slingram* is often applied to horizontal-loop systems but without any general agreement as to whether it is the fact that there are two mobile coils, or that they are horizontal and co-planar, or that they are linked by a reference cable, that makes the term applicable.

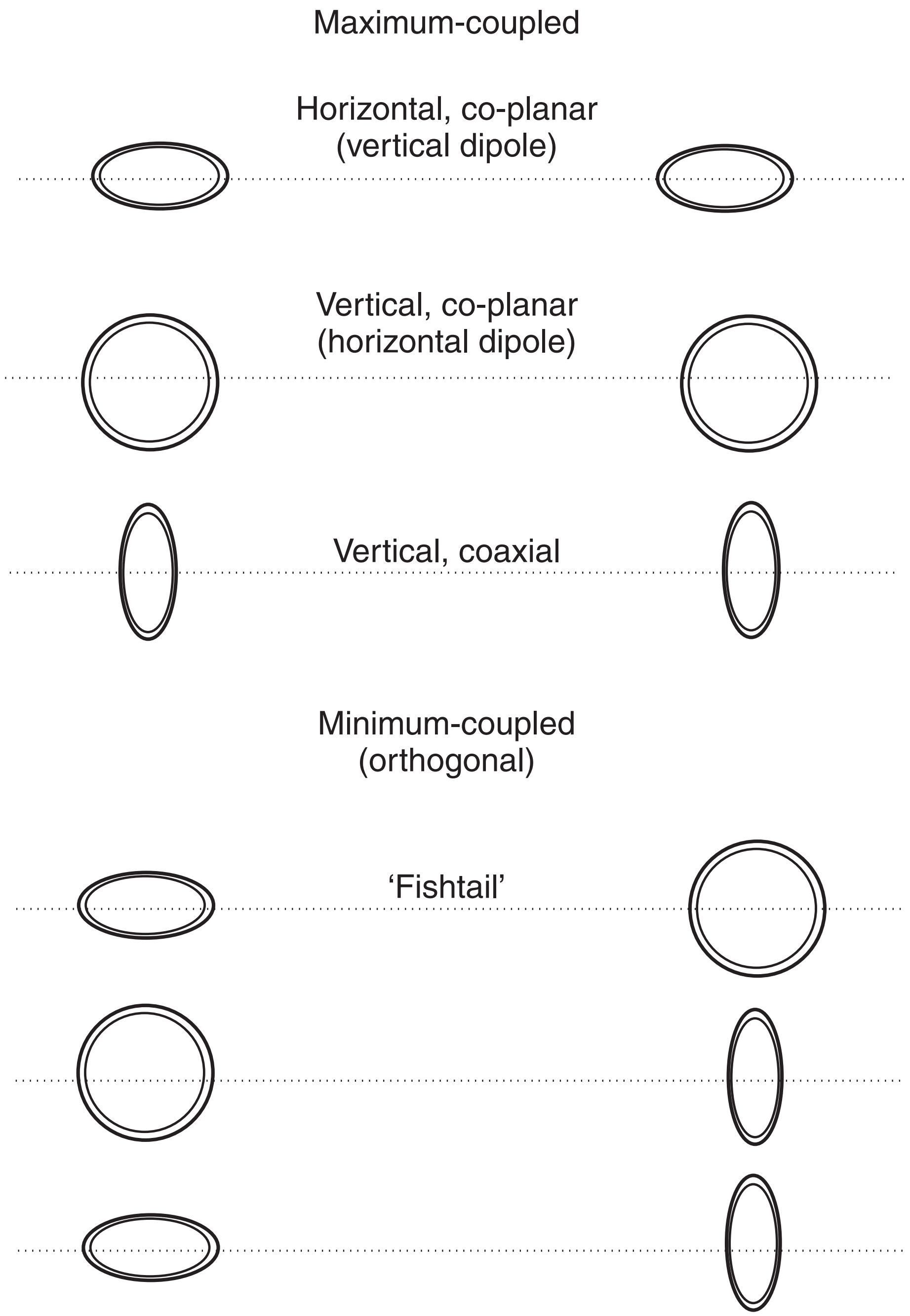


Figure 8.1 *Coil systems for electromagnetic surveys. The Geonics standard descriptions, in terms of magnetic dipole direction rather than loop orientation, are given in brackets. Relative orientation is variable in dip-angle systems, although usually the transmitter coil is held horizontal and the receiver coil is rotated to locate the direction for minimum signal.*

8.1.3 Response functions

In a Slingram survey, the electromagnetic *response* of a body is proportional to its mutual inductances with the transmitter and receiver coils and inversely proportional to its self-inductance, *L*, which limits eddy current flow. Anomalies are generally expressed as percentages of theoretical primary field and are therefore also inversely proportional to the mutual inductance between transmitter and receiver, which determines the strength of the primary field. The four parameters can be combined in a single *coupling factor,* $M_{ts}M_{sr}/M_{tr}L$.

Anomalies also depend on a *response parameter* which involves frequency, self-inductance (always closely related to the linear dimensions of the body) and resistance. Response curves (Figure 8.2) illustrate simultaneously how responses vary over targets of different resistivity using fixed-frequency systems and over a single target as frequency is varied. Note that the quadrature field is very small at high frequencies, where the distinction between good and merely moderate conductors tends to disappear.

Most single-frequency systems (except, as discussed in Section 8.1.8, those used for conductivity mapping) operate below 1000 Hz, and even the multi-frequency systems that are now the norm generally work entirely below 5000 Hz. Narrow poor-quality conductors may produce measurable anomalies only at the highest frequency or not at all (see Figure 9.10).

8.1.4 Slingram practicalities

The coil separation in a Slingram survey should be adjusted to the desired depth of penetration. The greater the separation, the greater the effective

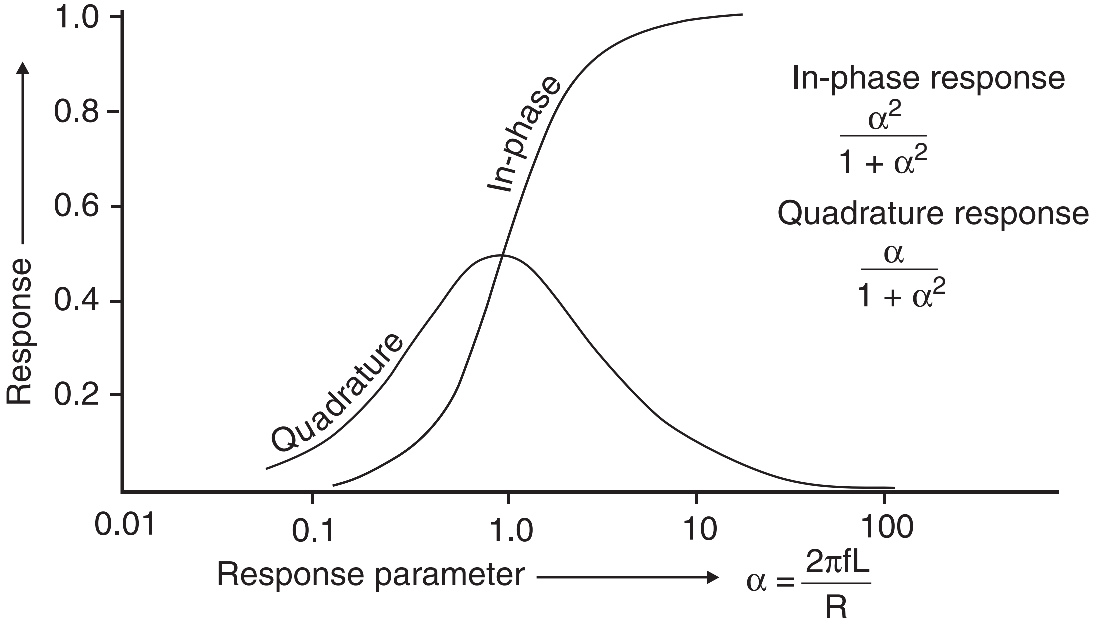


Figure 8.2 *Response of a horizontal-loop EM system to a vertical loop target, as a function of the response parameter (α). Note that the Response Parameter scale is logarithmic.* L *is the loop self-inductance,* R *its resistance and* f *is the frequency. The curves for more complex targets would have the same general form.*

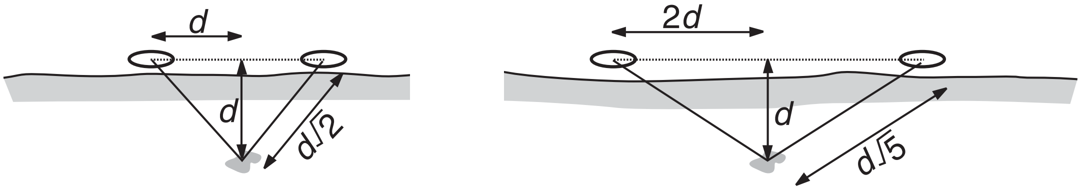


Figure 8.3 *Spacing and penetration. When the two coils are moved apart, the fractional change in distance between them is greater than between either and the conductor at depth. The increased separation thus increases the anomalous field as a percentage of the primary. In the example, doubling the separation increases the coil to target distances by about 60%.*

penetration, because the primary field coupling factor M_{tr} is more severely affected by the increase than are either M_{ts} or M_{sr} (Figure 8.3). The maximum depth of investigation of a Slingram system is often quoted as being roughly equal to twice the coil separation, provided that this is less than the skin depth (Figure 5.5) but this ignores the effects of target size and conductivity and may be unduly optimistic.

Because signals in Slingram surveys are referenced to primary field strengths, the *100% level* should be verified at the start of each day by reading at the standard survey spacing on ground which is level and believed to be non-anomalous. This check has to be carried out even with instruments that have fixed settings for allowable separations, because drift is a continual problem.

A check must also be made for any leakage of the primary signal into the quadrature channel (*phase mixing*). Instrument manuals describe how to test for this condition and how to make any necessary adjustments. Receivers and transmitters must, of course, be tuned to the same frequency for sensible readings to be obtained, but care is needed. A receiver can be seriously damaged if a transmitter tuned to its frequency is operated close by.

Figure 8.4 shows the horizontal-loop system anomaly over a thin, steeply dipping conductor. No anomaly is detected by a horizontal receiving coil immediately above the body because the secondary field there is horizontal. Similarly, there will be no anomaly when the transmitter coil is vertically above the body because no significant eddy currents will be induced. The greatest (negative) secondary field values will be observed when the conductor lies mid-way between the two coils. Coupling depends on target orientation and lines should be laid out across the expected strike. Oblique intersections produce poorly defined anomalies that may be difficult to interpret.

Readings obtained with mobile transmitter and receiver coils are plotted at the mid-points. This is reasonable because in most cases where relative coil orientations are fixed, the anomaly profiles over symmetrical bodies are also symmetrical and are not affected by interchanging receiver and transmitter.

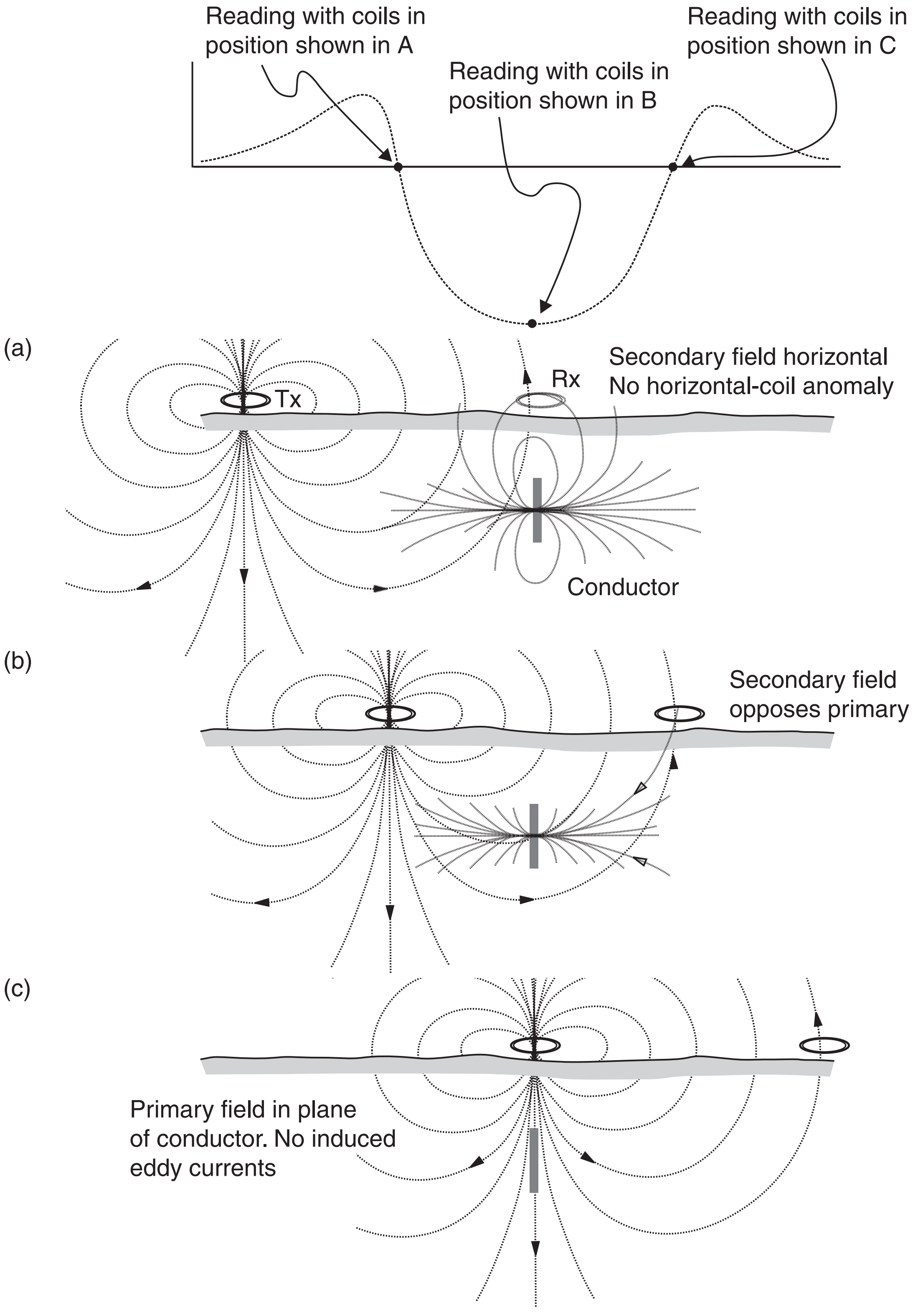


Figure 8.4 *Horizontal loop anomaly across a steeply dipping conductive sheet. Over a dipping sheet, the area between the side lobe and the distance axis would be greater on the down-dip side. Anomaly width is largely determined by coil separation, not by target width.*

Even where this is not completely true, recording mid-points is less likely to lead to confusion than recording either transmitter or receiver coil positions.

In all EM work, care must be taken to record any environmental variations that might affect the results. These include obvious actual conductors and also features such as roads, alongside which artificial conductors are often buried. Power and telephone lines cause special problems since they broadcast noise which, although different in frequency, is often strong enough to pass through the rejection (*notch*) filters. It is important to check that these filters are appropriate to the area of use (60 Hz in most of the Americas and 50 Hz nearly everywhere else).

Ground conditions should also be noted, since variations in overburden conductivity can drastically affect anomaly shapes as well as signal penetration. In hot, dry countries, salts in the overburden can produce surface conductivities so high that CW methods are ineffective and have been superseded by TEM.

8.1.5 Effects of coil separation

Changes in coupling between transmitter and receiver can produce spurious in-phase anomalies. The field at a distance r from a coil can be described in terms of radial and tangential components $F(r)$ and $F(t)$ (Figure 8.5). The amplitude factor A depends on coil dimensions and current strength.

For co-planar coils, $F(r)$ is zero because ϕ is zero and the measured field, F, is equal to $F(t)$. The inverse cube law for dipole sources then implies

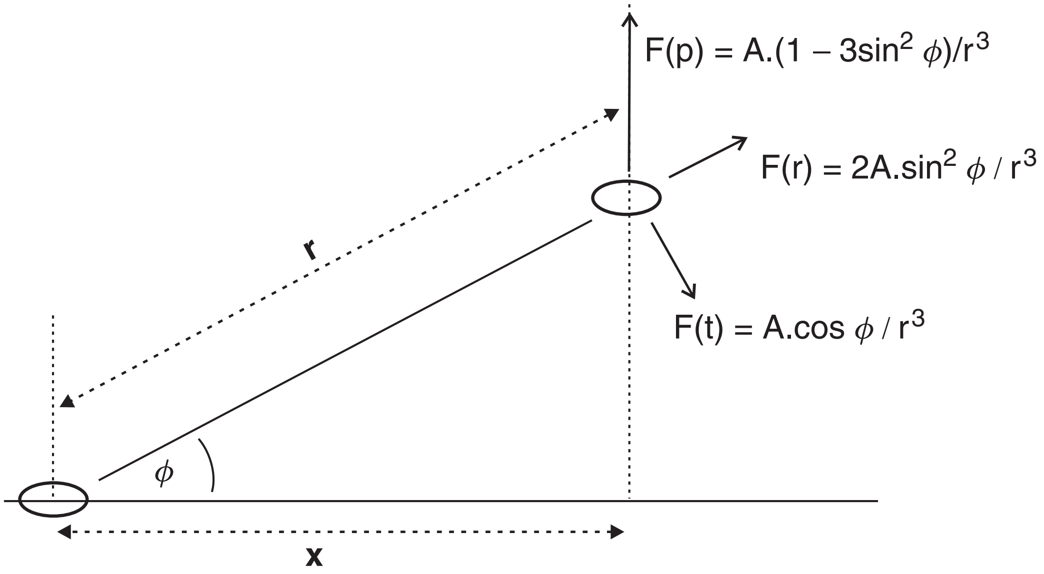


Figure 8.5 *Field components due to a current-carrying loop acting as a magnetic dipole source.* F(r) *and* F(t) *are radial and tangential components, respectively.* F(p)*, obtained by adding the vertical components of both, is the primary field measured by a horizontal receiver coil.*

that, for a fractional change x:

$$F = F_o/(1+x)^3$$

where F_o is the field strength at the intended spacing. If x is small, this can be written as:

$$F = F_o(1-3x)$$

Thus, for small errors, the percentage error in the in-phase component is three times the percentage error in distance. Since real anomalies of only a few percent can be important, separations must be kept very constant.

8.1.6 Surveys on slopes

On sloping ground, the distances between survey pegs may be measured either horizontally (*secant chaining)* or along slope (Figure 8.6). If along-slope distances are used in reasonably gentle terrain, coil separations should be constant but it is difficult to keep coils co-planar without a clear line of sight and simpler to hold them horizontal. The field $F(p)$ along the receiver axis is then equal to the co-planar field multiplied by $(1-3\sin^2\theta)$, where θ is the slope angle (Figure 8.7). The correction factor $1/(1-3\sin^2\theta)$ is always greater than 1 (coils really are maximum-coupled when co-planar) and becomes infinite when the slope is 35° and the primary field is horizontal (Figure 8.7).

If secant-chaining is used, the distances along slope between coils are proportional to the secant (=1/cosine) of the slope angle. For co-planar (tilted) coils the ratio of the 'normal' to the 'slope' field is therefore $\cos^3\theta$ and

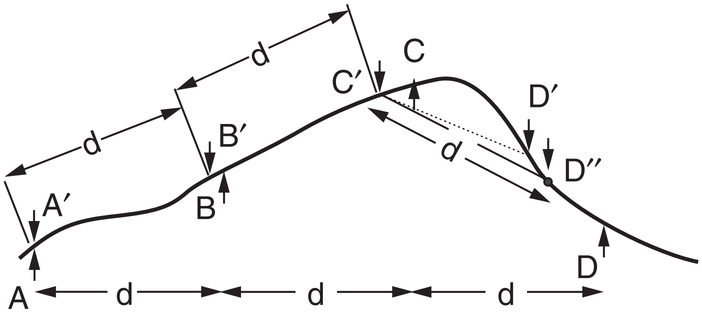


__Figure 8.6__ Secant chaining and slope chaining. Down arrows show locations of stations separated by intervals of d metres measured along slope. Up arrows show locations of secant-chained stations, separated by d metres horizontally. Between C and D, where topographic 'wavelength' is less than the station spacing, the straight line distance from C′ to D′ (for which separation was measured as the sum of short along-slope segments), is less than d. The 'correct' slope position is at D″.

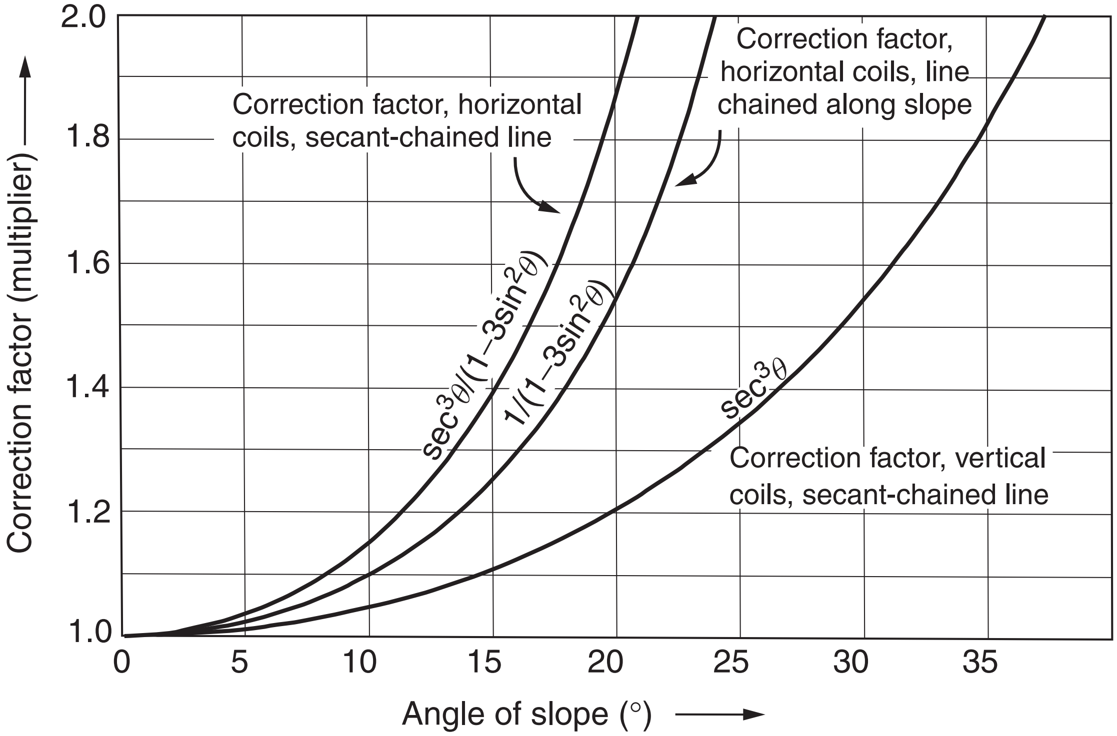


Figure 8.7 Slope corrections for a two-coil system calibrated for use in horizontal, co-planar mode. Readings should be multiplied by the appropriate factors.

the correction factor is $\sec^3\theta$. If the coils were to be held horizontal, the combined correction factor would be $\sec^3\theta/(1-3\sin^2\theta)$ (Figure 8.7).

Separations in rugged terrain can differ from their nominal values if the coil separation is greater than the distances over which slopes have been measured (Figure 8.6). Accurate surveying is essential in such areas and field crews may need to carry lists of the coil tilts required at each station. Instruments which incorporate tilt meters and communication circuits are virtually essential and even so errors are depressingly common and noise levels tend to be high.

8.1.7 Applying the corrections

For any coupling error, whether caused by distance or tilt, the in-phase field that would be observed with no conductors present can be expressed as a percentage of the maximum-coupled field F_o.

A field calculated to be 92% of F_o because of non-maximum coupling can be converted to 100% *either* by adding 8% *or* by multiplying the actual reading by 100/92. If the reading obtained actually were 92%, these two operations would produce identical results of 100%. If, however, there were a superimposed secondary field (e.g. if the actual reading were 80%), adding 8% would correct only the primary field (converting 80% to 88% and indicating the presence of a 12% anomaly). Multiplication would apply a correction to the secondary field also and would indicate a 13% anomaly. Neither procedure is actually 'right', but the principles illustrated in Figure 8.3 apply, i.e. the deeper the conductor, the less the effect of a distance error on the secondary field. Since any conductor that can be detected is likely to be quite near the surface, correction by multiplication is generally more satisfactory, but in most circumstances the differences will be trivial.

Coupling errors cause fewer problems if only quadrature fields are observed, since these are anomalous by definition (although, as Figure 8.2 shows, they may be small for very good as well as poor conductors). Rough corrections can be made using the in-phase multipliers but there is little point doing this in the field. The detailed problems caused by changes in coupling between a transmitter, a receiver and a third conductor can, thankfully, be left to the interpreter, provided the field notes describe the system configurations and topography precisely.

8.1.8 Ground conductivity measurement

Slingram-style systems are now being used for rapid conductivity mapping. At low frequencies and low conductivities, eddy currents are small, phase shifts are close to 90° and the bulk apparent resistivity of the ground is roughly proportional to the ratio between the primary (in-phase) and secondary (quadrature phase) magnetic fields. Relatively high frequencies are used to ensure a measurable signal in most ground conditions. If the *induction number*, equal to the transmitter–receiver spacing divided by the skin depth, is significantly less than unity, the depth of investigation is determined mainly by coil spacing.

Induced current flow in a homogeneous earth is entirely horizontal at low induction numbers, regardless of coil orientation, and in a horizontally layered earth the currents in one layer hardly affect those in any other. Figure 8.8 shows how current flow varies with depth for horizontal and vertical inducing coils in these circumstances. One reason for preferring horizontal coils (i.e. vertical dipoles) is obvious. The response for vertical co-planar coils, and hence the apparent conductivity estimate, is dominated by the surface layer.

The independence of current flows at different levels implies that the curves of Figure 8.8, which strictly speaking are for a homogeneous medium, can be used to calculate the theoretical apparent resistivity of a layered medium (Figure 8.9). Using this principle, layering can to some extent be investigated by raising or lowering the coils within the zero-conductivity air 'layer'. In principle it could also be investigated by using a range of frequencies, but the range would have to be very wide and inherently *broadband* methods such as TEM (Section 8.4) or CSAMT/MT (Section 9.4) are preferable.

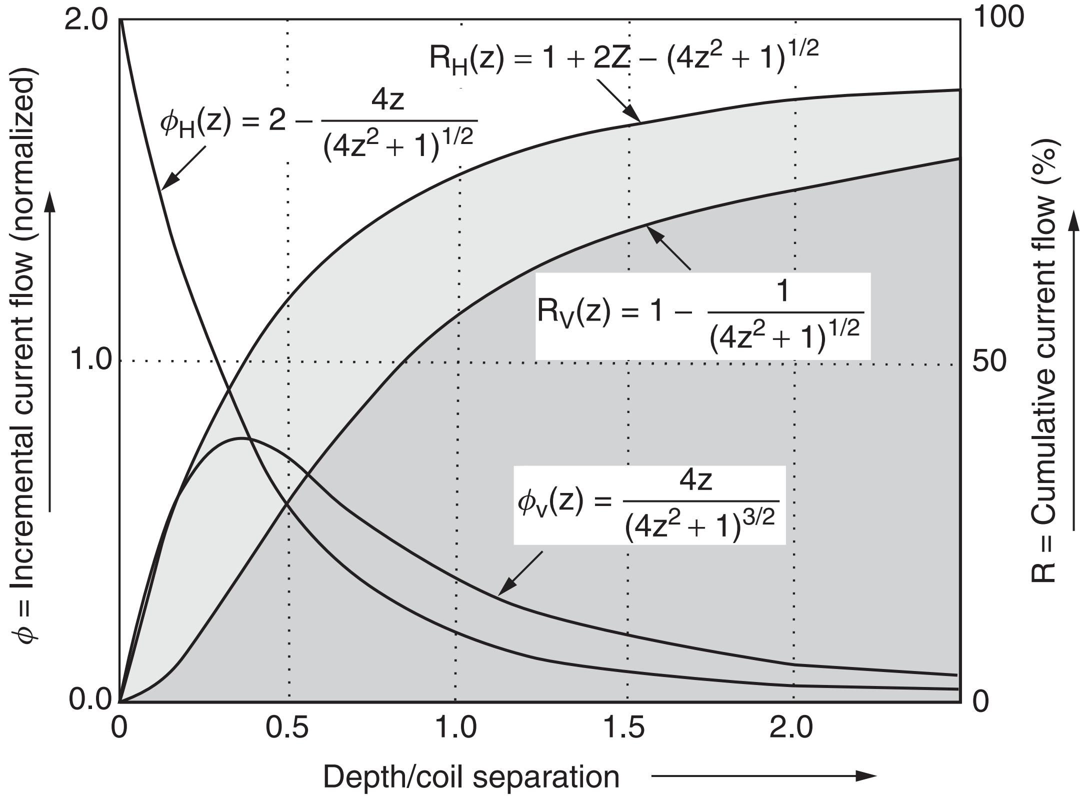


Figure 8.8 *Variation of induced current with depth in homogeneous ground, for co-planar coil systems operating at low induction numbers. 'Filled' curves show total current flowing in the region between the surface and the plane at depth, as a fraction of total current flow. Incremental curves are normalized. Subscripts 'h' and 'v' refer to horizontal and vertical dipoles, following the Geonics terminology used with the EM-31 and EM-34.*

The Geonics EM-31 (Figure 8.10) is an example of a co-planar coil instrument that can be used, at some risk to life and limb on difficult sites, by one operator to obtain rapid estimates of apparent resistivity (manmade conductors such as buried drums and cables may also be detected). Normally the coils are held horizontal giving, at low induction numbers, a penetration of about 6 m and a radius of investigation of about 3 m with the fixed 3.7 m coil spacing. This compares very favourably with the 20–30 m total length of a Wenner array with similar penetration (Section 6.1.3). Figure 8.11 shows the results of a very detailed EM-31 survey for sinkholes in chalk, carried out on top of a plastic membrane forming the lining of a small reservoir. Measurements can also be made (although not easily), with the coils vertical, halving the penetration. A shorter, and therefore more manoeuvrable version, the EM-31SH, is only 2 m long and therefore provides better resolution but only about 4 m of penetration.

Both versions of the EM-31 operate at 9.8 kHz. The more powerful, two-person, Geonics EM-34-3 (Figure 5.1e) uses frequencies of 0.4, 1.6 and

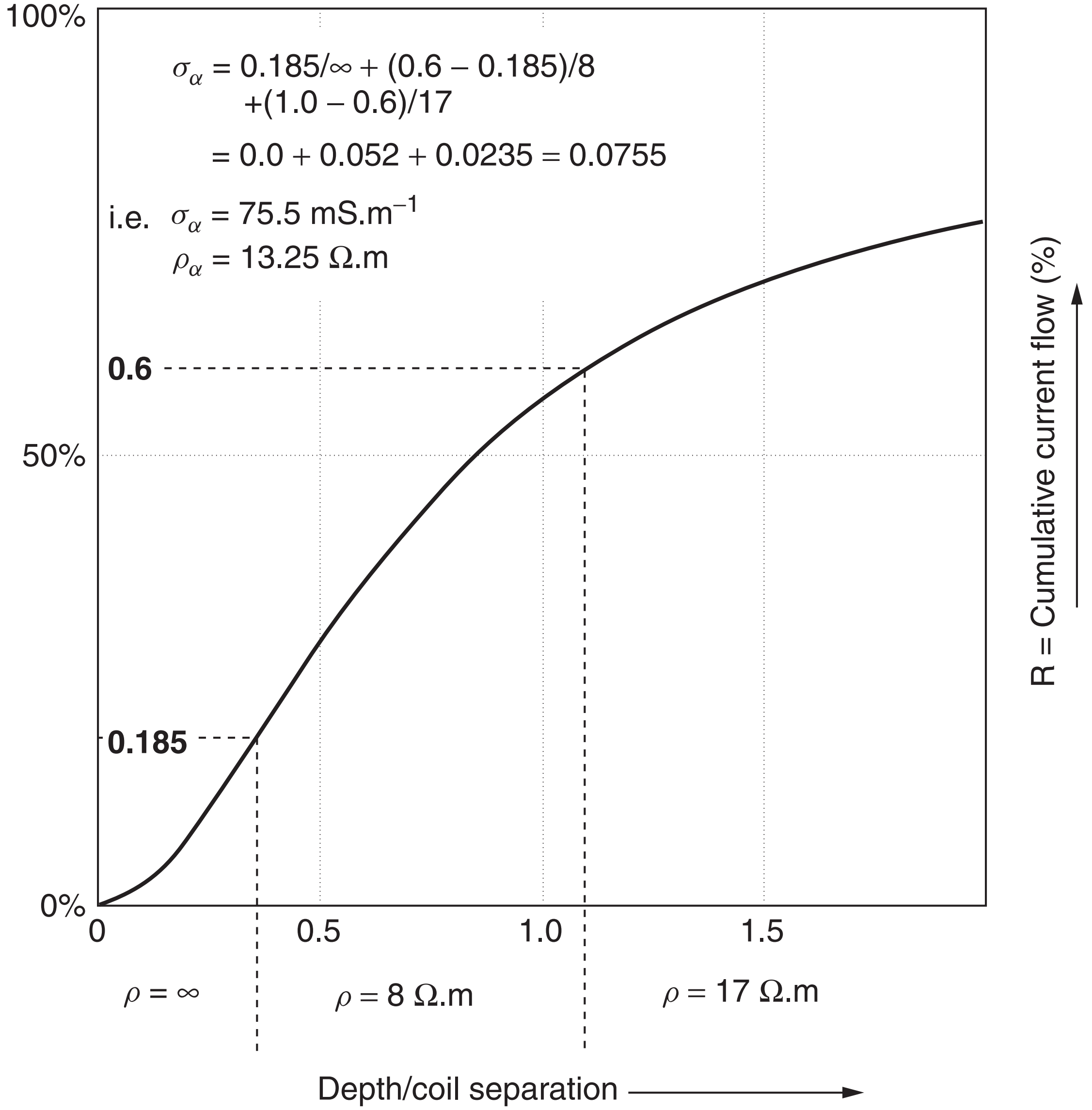


Figure 8.9 *Calculation of 'low induction number' apparent resistivity for a layered earth. The thickness of the first layer is determined by the height of the coils above the ground. This introduces an air layer with infinite resistivity and (in this example) a thickness of 1 m.*

6.4 kHz with spacings of 40, 20 and 10 m respectively. The frequency is quadrupled each time the coil separation is halved, so the induction number remains constant. Coil separation is monitored using the in-phase signal. Penetrations are 15, 30 and 60 m for horizontal coils and 7.5, 15 and 30 m for vertical coils. As with the EM-31, the EM-34-3 is calibrated to read apparent conductivity directly in $\mathrm{mS\,m^{-1}}$.

8.2 Other CWEM Techniques

CWEM surveys can be carried out using long-wire sources instead of coils and many different system geometries. These can only be considered very briefly.

Figure 8.10 *EM-31 in use in open country.*

8.2.1 Fixed-source methods

The fields produced by straight, current-carrying wires can be calculated by repeated applications of the *Biot–Savart law* (Figure 8.12). The relationship for four wires forming a rectangular loop is illustrated in Figure 8.13. If the measurement point is outside the loop, vectors that do not cut any side of the loop have negative signs.

The Slingram anomaly of Figure 8.4 was symmetrical because the receiver and transmitter coil were moved over the body in turn. If the source, whether a coil or a straight wire, were to be fixed, there would be a zero when a horizontal receiver coil was immediately above a steeply dipping body and the anomaly would be anti-symmetric (Figure 8.14). Fixed-source systems often measure dip angles or (which is effectively the same thing) ratios of vertical to horizontal fields.

Turam (Swedish: ‘two coil’) methods use fixed extended sources and two receiving coils separated by a distance of the order of 10 m. Anomalies are assessed by calculating *reduced ratios* equal to the actual ratios of the signal amplitudes through the two coils divided by the *normal* ratios that would have been observed over non-conductive terrain. Phase differences are measured between the currents in the two receiver coils and any non-zero value is

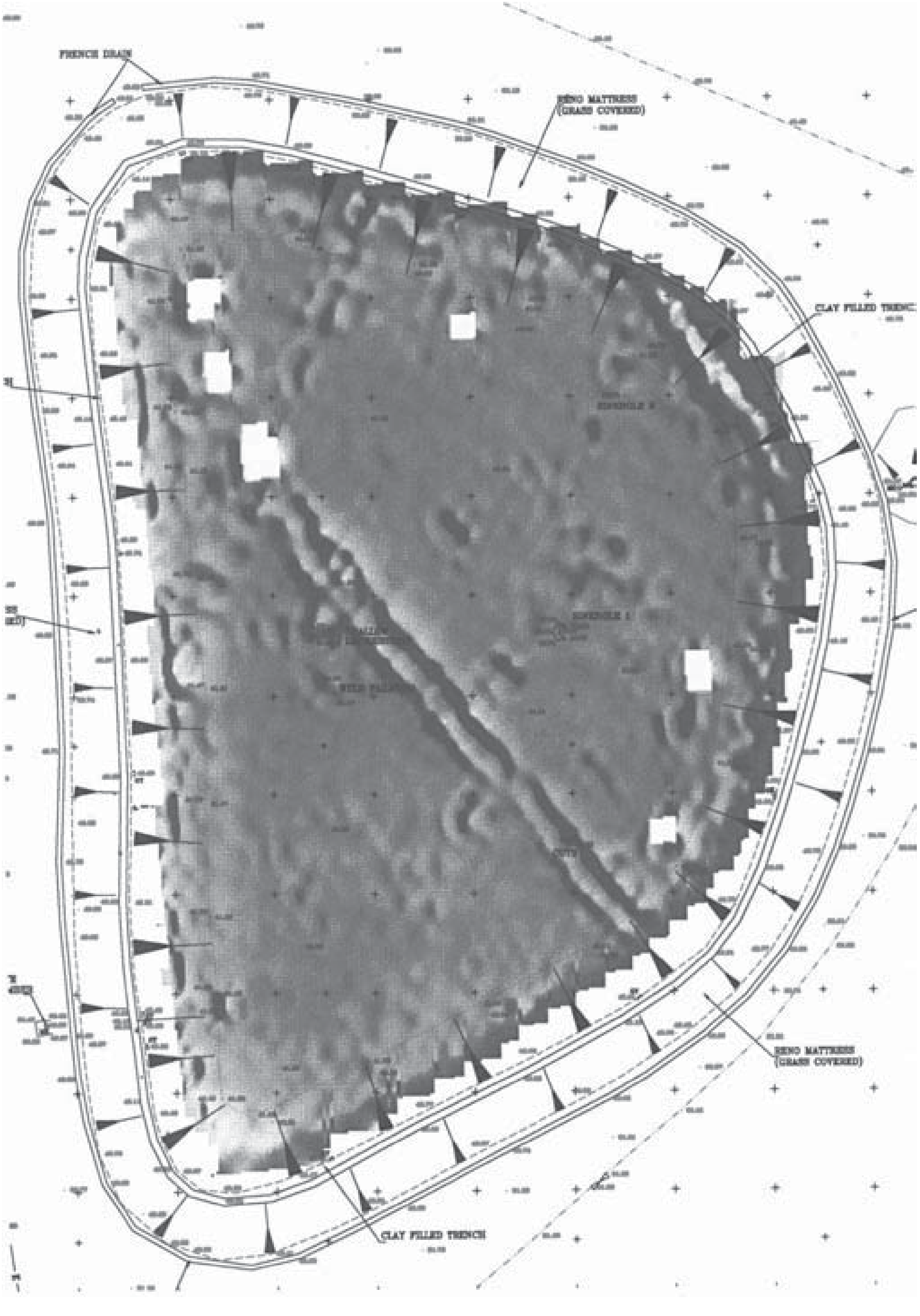
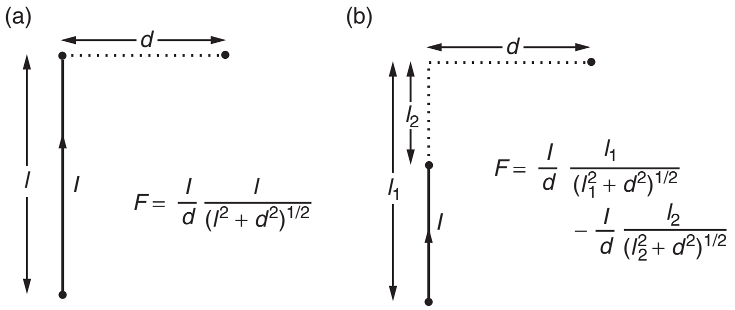


Figure 8.11 *Results of detailed EM-31 resistivity survey, plotted as an image. (Reproduced by permission of Geo-services International (UK) Ltd.)*

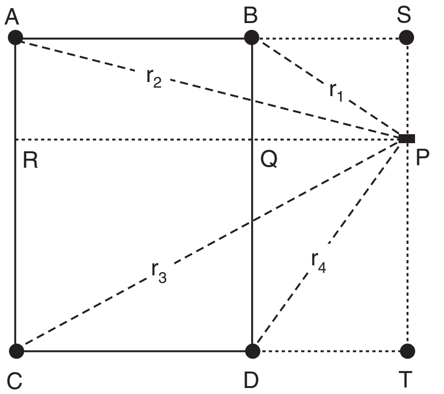
anomalous. There is no reference cable between receivers and transmitter, but absolute phases and ratios relative to a single base can be calculated provided that each successive reading is taken with the trailing coil placed in the position just vacated by the leading coil. CWEM Turam is now little used, but large fixed sources are common in TEM work.



$$F = \frac{I}{d}\,\frac{l}{(l^2 + d^2)^{1/2}}$$

$$F = \frac{I}{d}\,\frac{l_1}{(l_1^2 + d^2)^{1/2}} - \frac{I}{d}\,\frac{l_2}{(l_2^2 + d^2)^{1/2}}$$

Figure 8.12 *The Biot–Savart law. Any long-wire transmitter can be regarded as made up of elements of the type shown in (a). Two such elements, with currents in opposite directions, can be used to calculate cases such as (b) where the observation point is beyond the end of the wire.*



P is the point of observation
ABCD is the transmitter loop
A_1 is the area of PQBS
A_2 is the area of PRAS
A_3 is the area of PQBS
A_4 is the area of PQDT
I is the current in the loop

$$F = kI\left[\frac{r_1}{A_1} + \frac{r_2}{A_2} + \frac{r_3}{A_3} + \frac{r_4}{A_4}\right]$$

In this example r_1 and r_4 lie wholly outside the loop and must therefore be given negative signs

Figure 8.13 *Primary field due to a fixed, rectangular loop carrying a current* I. *If* I *is measured in amps and distances are in metres,* $k = 10^{-7}$ *for* F *in Weber·m*$^{-2}$.

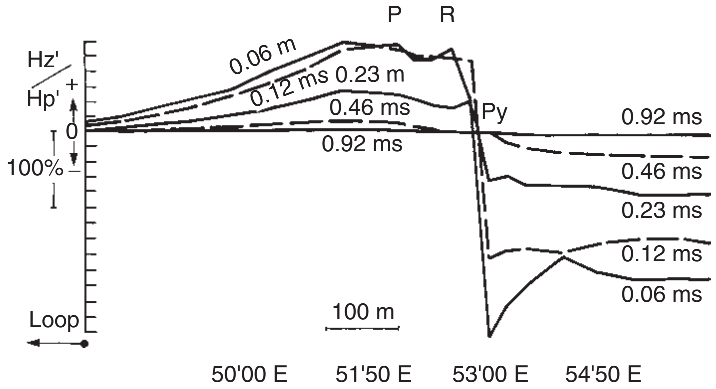


Figure 8.14 *Fixed-loop UTEM vertical component anomaly at Que River, Tasmania. Reading interval 25 m. The weak anomaly at P indicates economic mineralization, whereas the large anomaly at R is produced by barren pyrite. (Reproduced by permission of the Australian Society of Exploration Geophysicists.)*

8.3 Transient Electromagnetics

TEM systems provide multi-frequency data by repeated sampling of the transient magnetic fields that persist after a transmitter current is terminated. A modified square wave of the type shown in Figure 8.15 flows in the transmitter circuits, and transients are induced in the ground both on the upgoing and downgoing *ramps*. Observations are made on currents induced during the downgoing ramps only, since it is only these that can be measured in the absence of the primary field. It is therefore desirable that the up-ramp transients should be small and decay quickly, and the up-ramp is often *tapered*, reducing induction. In contrast, the current flow is terminated as quickly as possible, in order to maximize induction in the ground. This means that transmitter self-induction must be minimized, and single-turn loops are preferred to multi-turn coils.

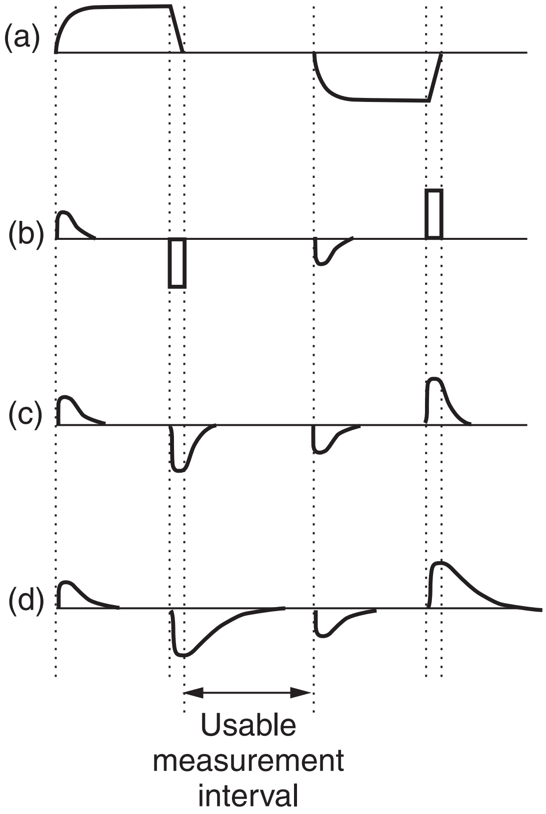


Figure 8.15 *TEM waveforms. (a) Transmitter waveform. Note the taper on the up ramp. The slope on the down ramp is drawn deliberately shallow, for clarity. (b) Signal induced in receiver due to primary field. (c) Signal induced in receiver due to currents circulating in a poor conductor. (d) Signal induced in receiver due to currents circulating in a good conductor. The beginning of the usable measurement interval is defined by the termination of the current induced by the primary, and the end by the beginning of the following up ramp.*

8.3.1 TEM survey parameters

A system in which the primary field is not present when secondary fields are being measured can use very high powers, and TEM systems are popular in areas where overburden conductivities are high and penetration is skin-depth limited. Since measurements are made when no primary field is present, the transmitter loop, which may have sides of 100 m or more, can also be used to receive the secondary field. Alternatively, a smaller receiver coil can be positioned within the loop. This technique can be used in CWEM surveys only with very large transmitter loops because of the strong coupling to the primary field.

It is also possible to carry out TEM ‘Slingram’ surveys, and most commercial systems can employ several different loop configurations. They differ in portability and, in detail, in sampling programs. The SIROTEM may be taken as typical. It produces a square-wave current with equal on and off times in the range from 23 to 185 msec. The voltage in the receiver coil can be recorded at 32 different times during eddy-current decay, and signals can be averaged over as many as 4096 cycles.

An alternative approach is provided by the UTEM system, in which current with a precisely triangular waveform and a fundamental frequency of between 25 and 100 Hz is circulated in a large rectangular loop. In the absence of ground conductivity, the received signal, proportional to the time derivative of the magnetic field, is a square wave. Deviations from this in the vertical magnetic and horizontal electric fields are observed by sampling at eight time delays.

In mineral exploration, TEM data are usually presented as profiles for individual delay times (Figure 8.14). The results at short delay times are dominated by eddy currents in large volume, relatively poor conductors. These attenuate quite rapidly, and the later parts of the decay curves are dominated by currents circulating in any very good conductors that may be present.

8.3.2 TEM depth sounding

TEM methods were originally developed to overcome some of the disadvantages of CWEM methods in mineral exploration but are now also being widely used for depth sounding. In homogeneous or horizontally layered ground, termination of current flow in the transmitter loop induces a similar current loop or ring in the adjacent ground. This current then decays, inducing a further current ring with a slightly greater radius at a slightly greater depth. The induced current thus progresses through the subsurface as an expanding ‘smoke ring’ (Figure 8.16), and the associated magnetic fields at progressively later times are determined by current flow (and hence by resistivity) at progressively greater depths. TEM surveys with 100 m transmitter loops have been used to obtain estimates of resistivity down to depths of several hundred metres, something requiring arrays several kilometres in length if conventional DC methods are used.

If localized good conductors, whether buried oil drums or sulphide orebodies, are present, the effects of the eddy currents induced in them will dominate the late parts of decay curves and may prevent valid depth-sounding data from being obtained. A relatively minor shift in position of the transmitter and receiver loops may be all that is needed to solve the problem.

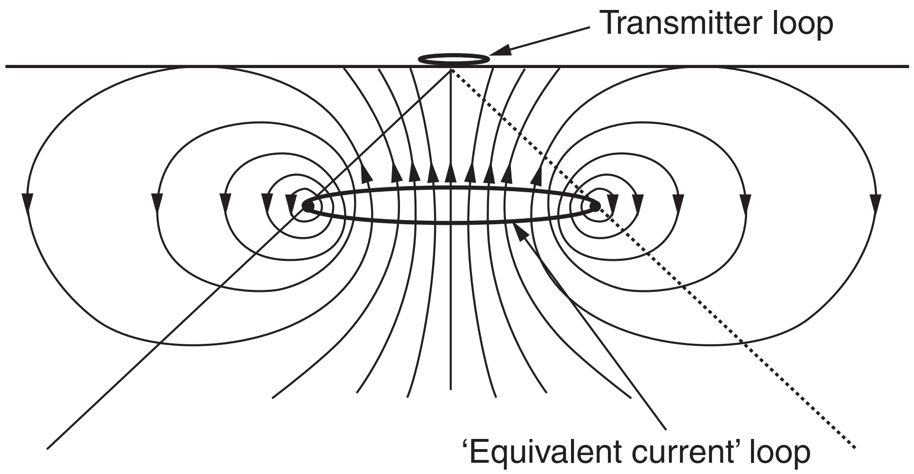


Figure 8.16 *The TEM 'expanding smoke ring' in a layered medium. The 'equivalent current loop' defines the location of maximum circulating current at some time after the termination of current flow in the transmitter loop. The slant lines define the cone within which the loop expands. Arrows are on lines of magnetic field.*

8.3.3 TEM and CWEM

CWEM and TEM methods are theoretically equivalent but have different advantages and disadvantages because the principal sources of noise are quite different.

Because noise in CWEM surveys arises mainly from variations in the coupling between transmitter and receiver coils, the separations and the relative orientations of the coils must either be kept constant or, if this is not possible, must be very accurately measured. The receiver circuitry must also be very precisely stabilized, but even so it is difficult to ensure that the initial 100% (for the in-phase channel) and 0% (for the quadrature channel) levels do not drift significantly during the course of the day. Because all these possible sources of noise are associated with the primary field, their effects cannot be reduced merely by increasing transmitter power. On the other hand, in TEM surveys the secondary fields due to ground conductors are measured at times when no primary field exists, and coupling noise is therefore negligible. The very sharp termination of transmitter current provides a timing reference that is inherently easier to use than the rather poorly defined maxima or zero-crossings of a sinusoidal wave, and the crystal-controlled timing circuits drift very little.

The most important sources of noise in TEM surveys are external natural and artificial field variations. The effect of these can be reduced by increasing the strength of the primary field and by N-fold repetition to achieve a $\sqrt{N}$ improvement in signal-to-noise ratio (Section 1.3.6). There are, however, practical limits to these methods of noise reduction. Transmitter loop