Chapter 10
Electromagnetic methods: introduction and principles

10.1 INTRODUCTION

10.1.1 Background

Among all the geophysical methods, the electromagnetic techniques must have the broadest range of different instrumental systems of any, matched by the remarkable range of applications to which these methods are being applied. These methods also show the greatest geographical diversity as some are used extensively and preferentially in the areas in which they were developed. For example, SIROTEM (see Section 11.3) is used predominantly in Australia where it was developed (named after the Australian Commonwealth Scientific Industrial Research Organisation, CSIRO), and Turam systems in

Sweden. The range of EM instruments manufactured by Geonics Ltd, Canada, has been used predominantly in North America, particularly eastern Canada, and now increasingly in Europe. There have been some major developments in the portability and ease of use of some instruments and their ensuing popularity has resulted in the techniques being used more widely. The interpretation methods available are largely dependent upon the instrumentation used for each survey and the information about the plethora of equipment available is widely scattered throughout the literature. However, the diversity of equipment provides a wide range of instruments to choose between in order to select the most appropriate tool for the task in hand. This, rather than being a disadvantage, is a major strength. Modern EM systems provide a very powerful suite of sophisticated instruments. Coupled with major advances in computer interpretation techniques, EM methods are set to become much more heavily used, especially for engineering and environmental applications.

Probably the first electromagnetic method to be used for mineral ore exploration was developed by Karl Sundberg in Sweden over two decades following the First World War (Sundberg 1931). What is now known as the Sundberg method was developed in 1925 and was also used in structural mapping in hydrocarbon exploration (Sundberg and Hedström 1934). Other pioneering work was done in the early 1930s by a Russian geophysicist V.R. Bursian, whose work is little known in the West. Other electromagnetic methods have been available commercially only since the Second World War and particularly since the mid-1960s. EM methods are especially important, not only in mineral and hydrocarbon exploration, but increasingly in environmental geophysics applications.

The different electromagnetic systems available are described briefly in Section 10.1.3 and in more detail in the next chapter. Chapter 12 is devoted to a discussion of 'ground penetrating radar' (GPR). A much more comprehensive and detailed discussion of the various electromagnetic methods, with the exception of ground penetrating radar, has been produced by Misac Nabighian (1987, 1991) and coauthors. Further discussions and descriptions of the various methods have been given in the three-volume treatise *Geotechnical and Environmental Geophysics* edited by Stan Ward (1990).

10.1.2 Applications

The range of applications of EM methods is large. It is dependent upon the type of equipment being used but can be broadly categorised as listed in Table 10.1. Not all EM methods are equally appropriate to the applications listed. For example, ground penetrating radar has very limited use in the direct investigation of landfills by virtue of the high ambient conductivity and the corresponding high attenuation of radiowaves with depth. Conversely, ground conductivity mapping

Table 10.1 The range of applications for EM surveying*

Mineral exploration
Mineral resource evaluation
Groundwater surveys
Mapping contaminant plumes
Geothermal resource investigations
Contaminated land mapping
Landfill surveys
Detection of natural and artificial cavities
Location of geological faults, etc.
Geological mapping
Permafrost mapping, etc.

* Independent of instrument type

does not have the required resolution in comparison with GPR in some archaeological investigations. Furthermore, GPR can be used with care inside buildings, while ground conductivity methods cannot by virtue of interference from ambient electrical noise from mains power lines, etc.

One of the main advantages of the EM methods is that the process of induction does not require direct contact with the ground, as in the case of electrical methods where electrodes have to be planted into the ground surface (see Chapter 7). Consequently, the speed with which EM surveys can be made is much greater than an equivalent survey using contacting electrical resistivity. Furthermore, the induction process also allows the method to be used from aircraft and ships, as well as down boreholes. Similar to electrical resistivity methods, scale model experiments can be undertaken to illustrate particular structures (e.g. Frischknecht 1987). However, numerical models may be used preferentially (Hohmann 1987) but still require large amounts of computing time, and are limited by the computational difficulties in defining especially two- and three-dimensional models. Aspects of the limitations of computer analysis are discussed in more detail in the next chapter.

10.1.3 Types of EM systems

Electromagnetic methods can be classified as either time-domain (TEM) or frequency-domain (FEM) systems. Frequency-domain instruments use either one or more frequencies whereas time-domain equipment makes measurements as a function of time. EM methods can be either passive, utilising natural ground signals (e.g. magnetotellurics) or active, where an artificial transmitter is used either in the near-field (as in ground conductivity meters) or in the far-field (using remote high-powered military transmitters as in the case of VLF mapping).

Table 10.2 A classification of electrical and electromagnetic systems

Transmitter type	Receiver type			
	Ground wire	Both wire and small coil	Small coil (ground)	Small coil (air)
Grounded wire				
Galvanic	Resistivity IP		Magnetometric resistivity (MMR) Magnetic IP (MIP)	
Inductive		CSAMT	Some TEM systems	
Small loop			Slingram Horizontal-loop EM Vertical-loop EM Tilt-angle method Ground conductivity meters (GCM) Some TEM systems Coincident loop Borehole systems	Airborne EM Time-domain towed-bird Helicopter rigid-boom
Large loop (long wire)			Large-loop systems Sundberg method Turam Many TEM systems Borehole systems	
Plane wave				
Vertical antenna		VLF-resistivity VLF		VLF
Natural geomagnetic field	Telluric currents			

Grounded wires measure potential difference per length, thus electric field. Coils (or fluxgate magnetometers or SQUIDS) measure magnetic field, or its time derivative. A small loop is a 3-D source (magnetic dipole). A long wire (or the long edge of a large loop) is a 2-D source. Natural EM sources are assumed to be 1-D sources. Receivers can be frequency-domain, time-domain (TEM), or both, CSAMT = controlled-oource audio magneto-telluric. This classification, which excludes the high-frequency techniques (radar, etc.), is based on Swift (1988, Table 1, p. 6)

A basic classification of EM systems is given in Table 10.2, which is based on Swift (1988). Each system is described briefly in this section; VLF, ground-conductivity, time-domain EM, telluric and magnetotelluric systems are described in more detail in Chapter 11. Ground penetrating radar is discussed comprehensively in Chapter 12.

Case histories are given where appropriate to illustrate the use of each of the main techniques. In most cases, the concept of each method is described rather than specific equipment systems which may change through continuing development work.

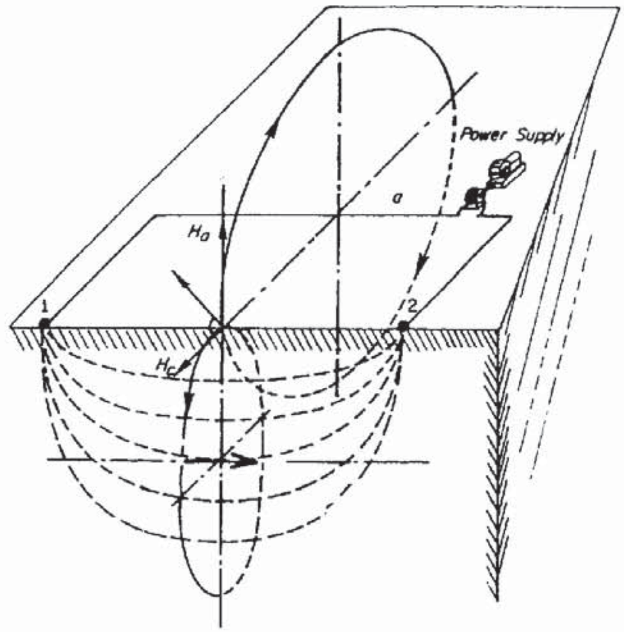

Figure 10.1 Basic concept of a magnetometric resistivity (MMR) field survey layout. Electrodes (1 and 2) are used to inject direct current into the ground. The secondary magnetic field arising from the current flow in the ground is measured at the mid-point by an extremely sensitive magnetometer. Reproduced with permission from Edwards and Nabighian (1991).

The term 'galvanic' used in Table 10.2 describes the injection of electrical current directly into the ground via electrodes; these methods are discussed in detail in Chapters 7 and 9.

10.1.3.1 Magnetometric resistivity (MMR)

Commutated direct current is injected into the ground through two widely separated electrodes. The anomalous conductivity contribution is determined at the midpoint by measuring the secondary magnetic field arising from the flow of current using an extremely sensitive low-noise magnetometer aligned perpendicular to the line between the electrodes (Figure 10.1). For further details, see Chapter 7 and, in particular, the review by Edwards and Nabighian (1991).

10.1.3.2 Small-loop systems

A frequency-domain EM system in which two small coils, one a transmitter and the other a receiver, separated by a constant distance of between 4 m and 100 m, are moved along a survey transect. The primary field is nulled so that the in-phase and quadrature components of the secondary field can be measured. The various combinations of coil orientation are shown in Figure 10.2. Slingram is synonymous with the *horizontal-loop method* (HLEM), Boliden, EM Gun, MaxMin and with Ronka EM methods. *Ground conductivity meters* (GCM) can be classified as being of this type of method. In this case, the quadrature component is normally taken to be a linear measure of the apparent conductivity of the ground; the coplanar

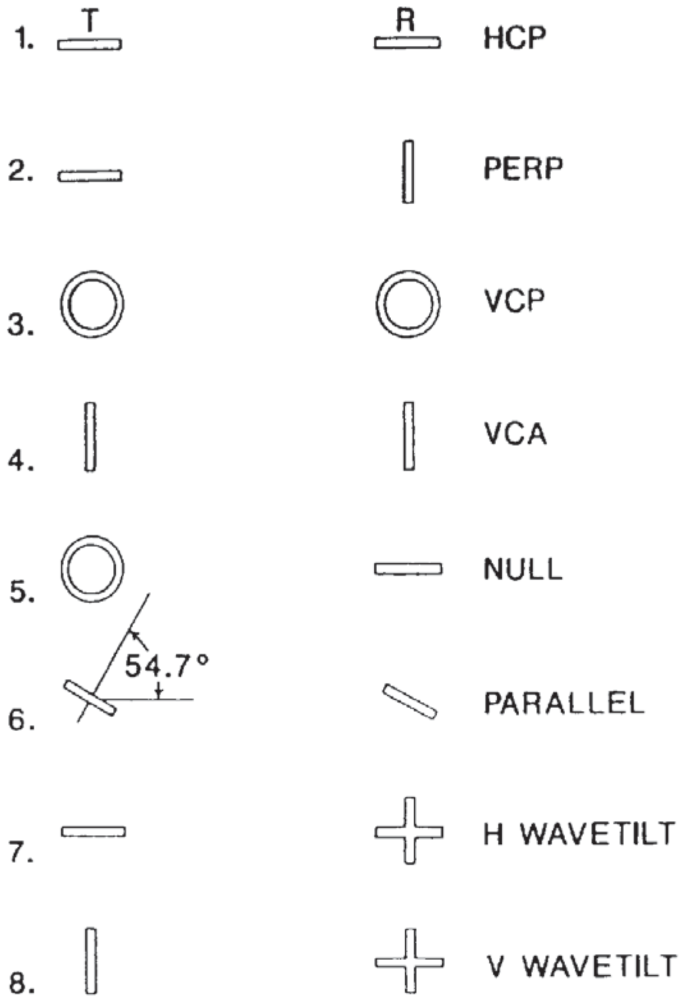

Figure 10.2 Eight common dipolar loop configurations (T*x* = transmitter; R*x* = receiver). Each rectangle represents the edge-on view of a coil; e.g. to move from configuration 1 to 3, both coils are rotated about a horizontal axis; to move from 3 to 4, each coil is rotated about a vertical axis. HCP = horizontal coplanar; VCP = vertical coplanar; VCA = vertical coaxial; PERP = perpendicular. Reproduced with permission from Frischnecht *et al.* (1991).

coils are deployed both horizontally and vertically; Chapter 11 has more details. For a detailed discussion of small-loop systems, see the review by Frischknecht *et al.* (1991).

10.1.3.3 Large-loop systems

There are two basic configurations in this classification, namely, the original method known as Sundberg's method, and the other, Turam.

Sundberg's method uses a long, grounded, insulated wire a few hundred metres to several kilometres long, or a rectangular loop with the long-side laid in the direction of geological strike (Figure 10.3A and B). Typical loop dimensions are 1200 m by 400 m. Measurements are made along profiles at right-angles to the cable or long side of the loop. Phase reference is taken by using a feeding coil located close to the source loop/cable using the compensator system shown in Figure 10.3C. Normally, only the vertical magnetic field is observed using the receiver coil. If the coil is deployed in three mutually perpendicular planes, then the EM field can be determined completely.

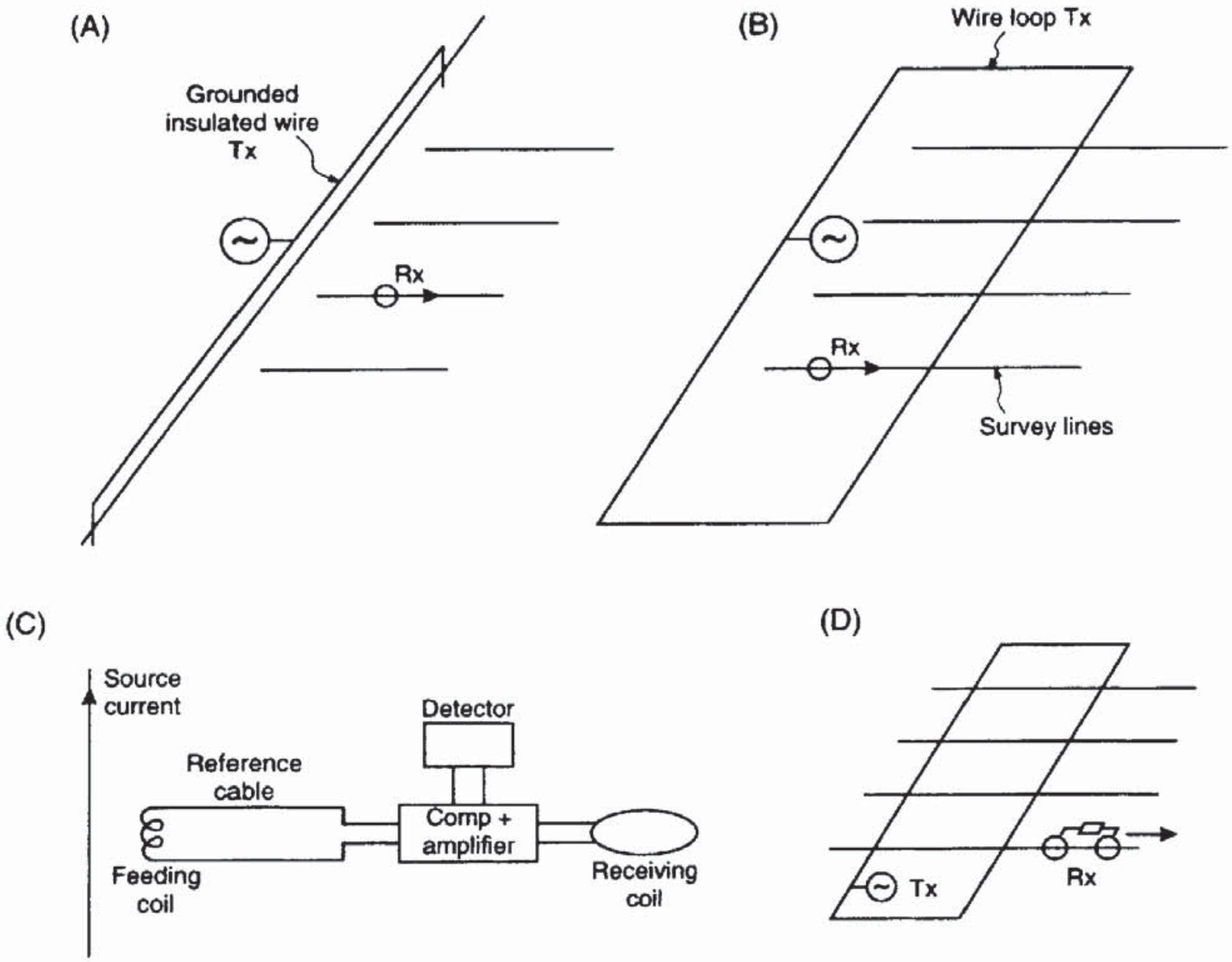

Figure 10.3 (A) Survey layout for the Sundberg method with a long grounded wire, or (B) a grounded wire loop with survey profile lines indicated. Phase reference is determined using a compensator (C) close to the source wire. In the Turam method (D), two separate receiver coils are deployed with a constant separation

The Turam technique overcomes a significant operational difficulty with the Sundberg method, i.e. the necessity to have a feeding coil close to the source cable/loop. In the Turam method, two separate receiver coils are used which are maintained at a constant separation, typically 10–20 m (Figure 10.3D). After each measurement, the coils are moved so that the rear coil then takes the position formerly occupied by the forward one, and so on along the transect. The two coils provide a means whereby a measurement is made of the ratio of the resultant vertical-field amplitudes and phase difference of the vertical fields at two neighbouring points. In effect, by having a constant coil separation and measuring parameters at each of the two locations, the horizontal gradient of phase of the resultant vertical field is determined. A more complete discussion of these two methods has been given by Parasnis (1991).

10.1.3.4 Time-domain systems

If a continuous EM field is produced by a transmitter, the secondary field is either determined by nulling the primary field so as to be able to detect the secondary field, or by measuring the resultant of both primary and secondary fields, and hence computing the secondary field parameters; those of the primary field are known by design. In time-domain or transient EM, the primary field is applied in pulses, typically 20–40 ms long, with the secondary field being measured once the primary field has been switched off over the following 100 ms, for example. One advantage of this is that the transmitter coil can also be used as the receiver. The basic field layouts are shown in Figure 10.4.

Typically a large ungrounded coil, through which a strong direct current is passed, is laid on the ground with the long axis parallel to

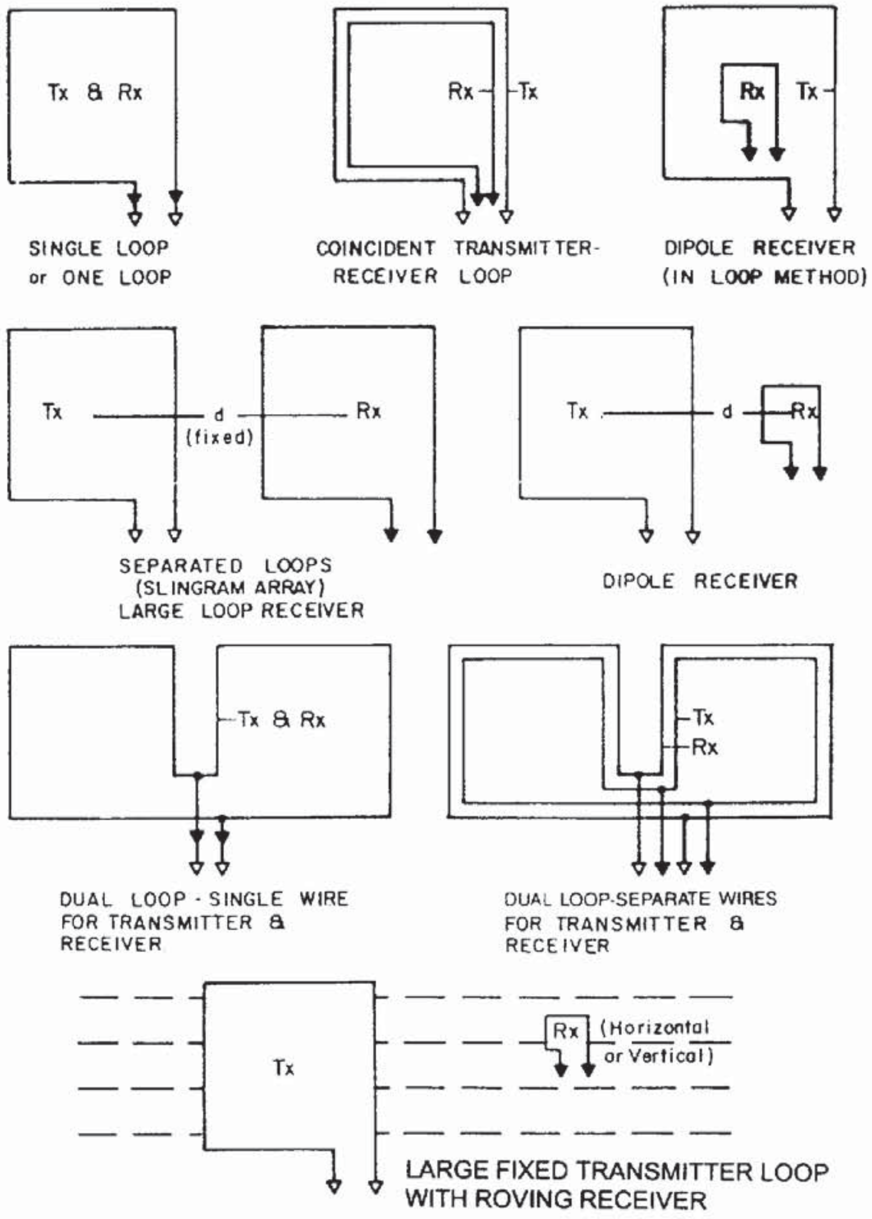

Figure 10.4 Field configurations for time-domain EM surveys. Reproduced with permission from Nabighian and Macnae (1991).

any geological strike. A small receiver coil is moved along transects perpendicular to the long axis of the ungrounded loop to obtain profiles of the measured parameters as a function of distance along the transect. Alternatively, instead of profiling, TEM systems can be used very effectively for depth soundings. Increased depth penetration is achieved by measuring the decay of the secondary field as a function of time. As the secondary field decays, the field parameters are measured at discrete time intervals (typically logarithmically arranged). It is analogous to the induced polarisation (IP) method in resistivity surveying. A specific system (INPUT) was developed in 1958 for airborne work (Barringer 1962). Following 1970, with improvements in technology and computing capabilities, a range of EM systems were developed by both academic institutions and commercial companies. By 1988, all instrument manufacturers had provided fully digital TEM systems.

As a guide, but depending upon the actual configurations and equipment being used, 50 TEM soundings per day is not unreasonable. With increasing pressure to use TEM in environmental applications where depths of penetration of less than 50 m are required, 'very-early TEM' (VETEM) systems are being developed. VETEM could be used in surveys where depths of penetration of less than 25 m but high vertical resolution are required, such as over closed landfills. For more detailed descriptions of TEM systems and of depth sounding, see the reviews by Nabighian and Macnae (1991) and by Spies and Frischknecht (1991) respectively.

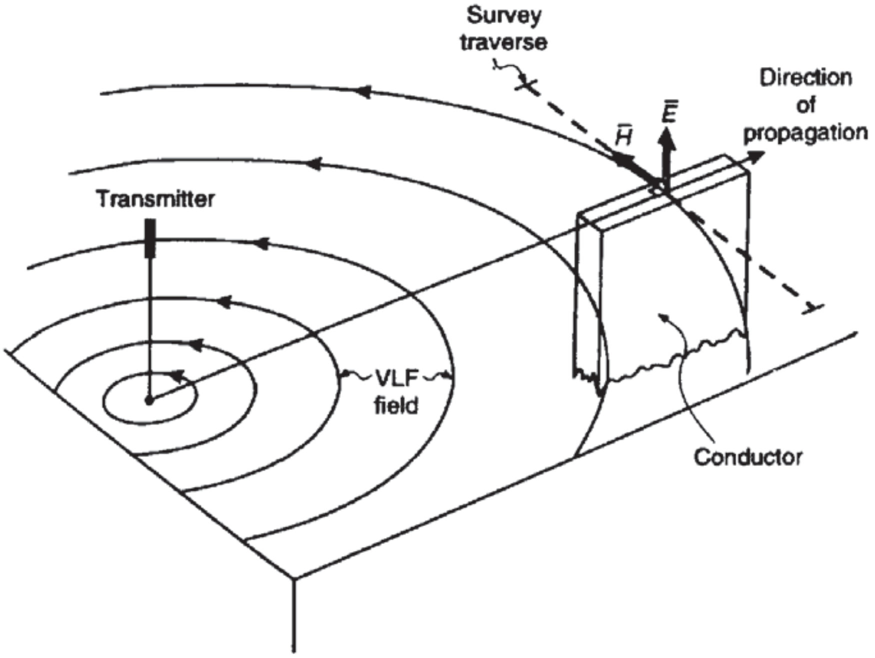

Figure 10.5 Artificial VLF source (e.g. military transmitter) provides a primary EM field which, at a sufficiently large distance, equates to a plane EM wave. Preferred survey directions over a linear conductor are tangential to the VLF field

10.1.3.5 Very low frequency (V.L.F)

High-powered military radio transmitters operating in the 15–24 kHz range (i.e. very low frequency in radio terms) are used to communicate with submarines even when submerged, and for long-range radio positioning. At very large distances from the transmitters, the EM field approximates to a plane wave which is used in geophysical exploration (Figure 10.5). The method can be used either on the ground or from aircraft. The method is discussed in more detail in the next chapter and has been reviewed by McNeill and Labson (1991).

10.2 PRINCIPLES OF EM SURVEYING

10.2.1 Electromagnetic waves

Electromagnetic methods use the response of the ground to the propagation of incident alternating electromagnetic waves which are made up of two orthogonal vector components, an electric intensity (***E***) and a magnetising force (***H***) (Figure 10.6), in a plane perpendicular to the direction of travel. An electromagnetic field can be generated by passing an alternating current through either a small coil comprising many turns of wire or a large loop of wire. The frequency range of electromagnetic radiation is very wide (Figure 10.7), from atmospheric micropulsations at a frequency less than 10 Hz, through the radar bands (10^8 to 10^{11} Hz) up to X-rays and gamma-rays at frequencies in excess of 10^{16} Hz. Of critical importance is the visible band ($\approx 10^{15}$ Hz).

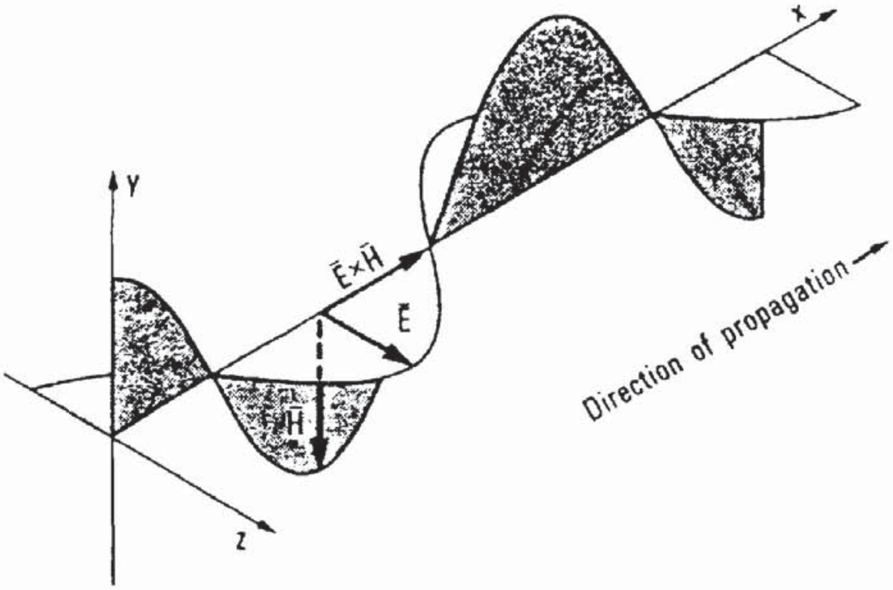

Figure 10.6 Basic elements of an electromagnetic wave, showing the two principal electric (***E***) and magnetic (***H***) components. Reproduced with permission from Beck (1981)

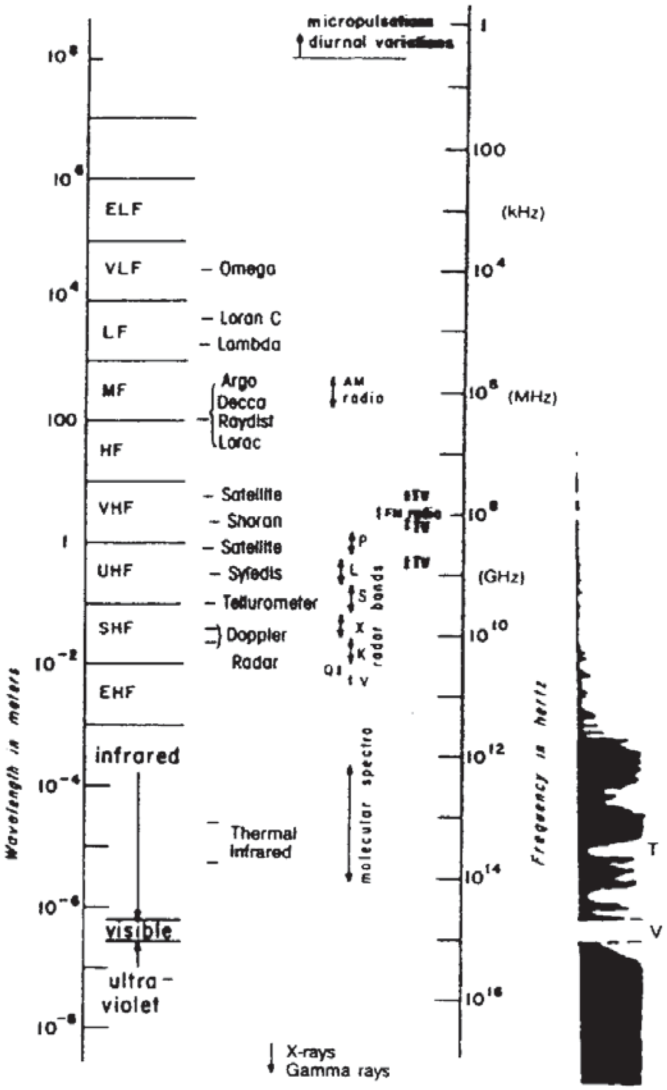

Figure 10.7 The electromagnetic spectrum. (A) designation of the various parts of the spectrum as a function of wavelength in metres. In (B), the dark portion of the graph shows zones of attenuation due to atmospheric absorption. Two windows are evident in the absorption spectrum at T (thermal infrared) and V (visible light). Reproduced with permission from Sheriff (1991)

For geophysical applications, frequencies of the primary alternating field are usually less than a few thousand hertz. The wavelength of the primary wave is of the order of 10–100 km while the typical source–receiver separation is much smaller (≈ 4–100 + m). Consequently, the propagation of the primary wave and associated wave attenuation can be disregarded (Figure 10.8).

In general, a transmitter coil is used to generate the primary electromagnetic field which propagates above and below ground. When the EM radiation travels through sub-surface media it is modified slightly relative to that which travels through air. If a conductive medium is present within the ground, the magnetic component of the incident EM wave induces eddy currents (alternating currents) within the conductor. These eddy currents then generate their own, secondary, EM field which is detected by a receiver

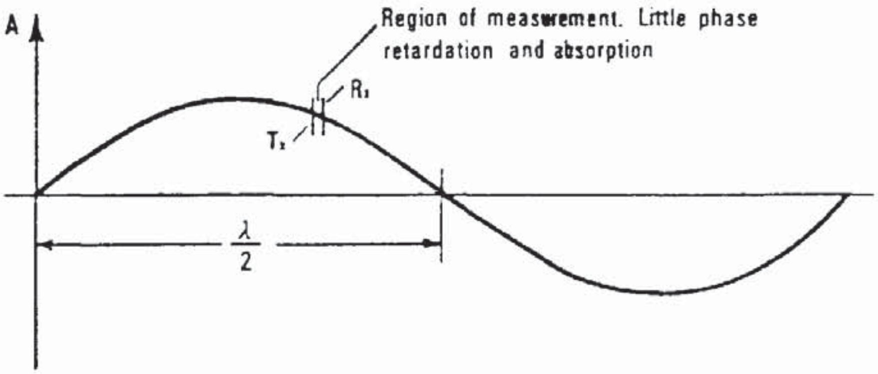

Figure 10.8 The physical separation of a transmitter (T*x*) and receiver (R*x*) is very small in relation to the wavelength of EM waves with frequencies greater than 3 kHz. Consequently, attenuation due to wave propagation can be ignored. Reproduced with permission from Beck (1991)

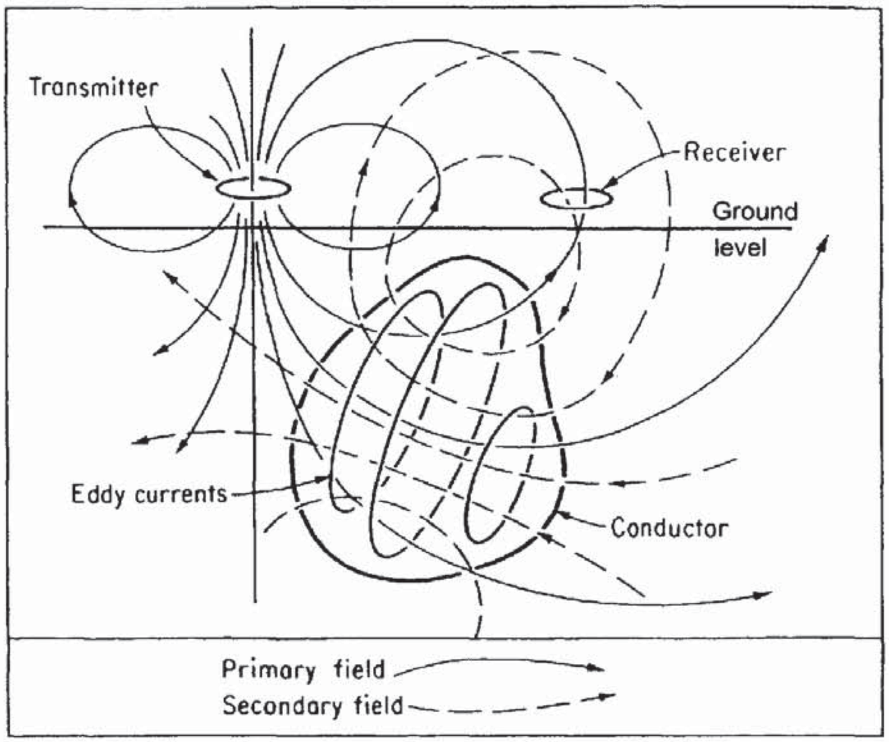

Figure 10.9 Generalized schematic of the EM surveying method. Reproduced with permission from Grant and West (1965)

(Figure 10.9). The receiver also detects the primary field which travels through the air, so the overall response of the receiver is the combined (resultant) effect of both the primary and the secondary fields. Consequently, the measured response will differ in both phase and amplitude relative to the unmodulated primary field. The degree to which these components differ reveals important information about the geometry, size, and electrical properties of any sub-surface conductor. Detailed discussions of electromagnetic theory, which are beyond the scope of this book, have been given by Grant and West (1965), Telford *et al.* (1990), and Ward and Hohmann (1991), among others.

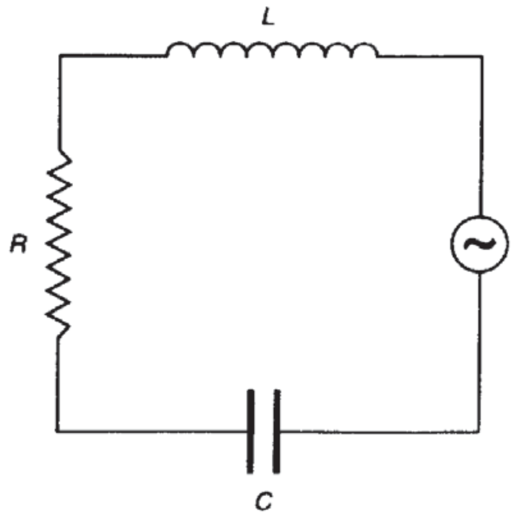

Figure 10.10 Basic electrical circuit containing capacitance (C), inductance (L) and resistance (R), the three electrical components that describe the equivalent behaviour of the ground.

It is useful to regard the ground under investigation as comprising three components: inductive (L), resistive (R) and capacitive (C); the electrical circuit equivalent is shown in Figure 10.10. The applied alternating voltage has the form of a sine wave with an angular frequency of ω ($= 2\pi f$) and amplitude E_0 which varies as a function of time as described mathematically in Box 10.1. The current (I) which flows lags behind the applied voltage by an amount α, the phase lag. In EM exploration, a primary magnetic field is applied (P) which, in accordance with the properties of an EM wave, is in phase with its orthogonal electric component (E) (refer to Figure 10.6). Consequently, the form of the primary magnetic wave is $P = H_0 \sin \omega t$, where H_0 is the peak amplitude of the magnetic wave (Figure 10.11A). The voltage induced into a secondary perfect conductor as a result of the incident primary magnetic field lags behind the primary field by $\pi/2$.

According to Faraday's Law of EM induction, the magnitude of the induced voltage is directly proportional to the rate of change of the magnetic field. The induced voltage is directly proportional to the rate of change of the magnetic field. The induced voltage will be zero when the magnetic field is either at its maximum or minimum (Figure 10.11B). Eddy currents within a conductor take a finite time to generate, arising from an induced voltage. This generation time is manifest as the phase lag α (Figure 10.11C) which depends upon the electrical properties of the conductor. In good conductors this phase lag can be large, and conversely in poor conductors the phase lag is small. Once generated the secondary magnetic field interacts with the primary to form a resultant magnetic field (Figure 10.11D) which has a total phase lag (ϕ) behind the primary field.

Box 10.1 Time varying electrical field

The amplitude (E) of an alternating voltage is given by:

$$E = E_0 \sin \omega t.$$

The current (I) within the equivalent circuit (see Fig. 10.10) is described by:

$$I = E_0\{[\omega L - (1/\omega C)]^2 + R^2\}^{-1/2} \sin(\omega t - \alpha)$$

where

$$\alpha = \tan^{-1}[\omega L - (1/\omega C)]/R$$

and L is the inductance, C the capacitance and R the resistance.

The relationship between the primary, secondary and resultant fields can be represented in vector form (Figure 10.12A). The real (or in-phase) and imaginary (out-of-phase, or quadrature) components are shown on the vector diagram. The primary magnetic field is designated ***P*** and relates to the time-varying wave shown in Figure 10.11A. The induced voltage (cf. Figure 10.11B) lags $\pi/2$ (90°) behind the primary and the secondary current or magnetic field lags behind by α (cf. Figure 10.11C) and has a magnitude ***S***. By normal conven-

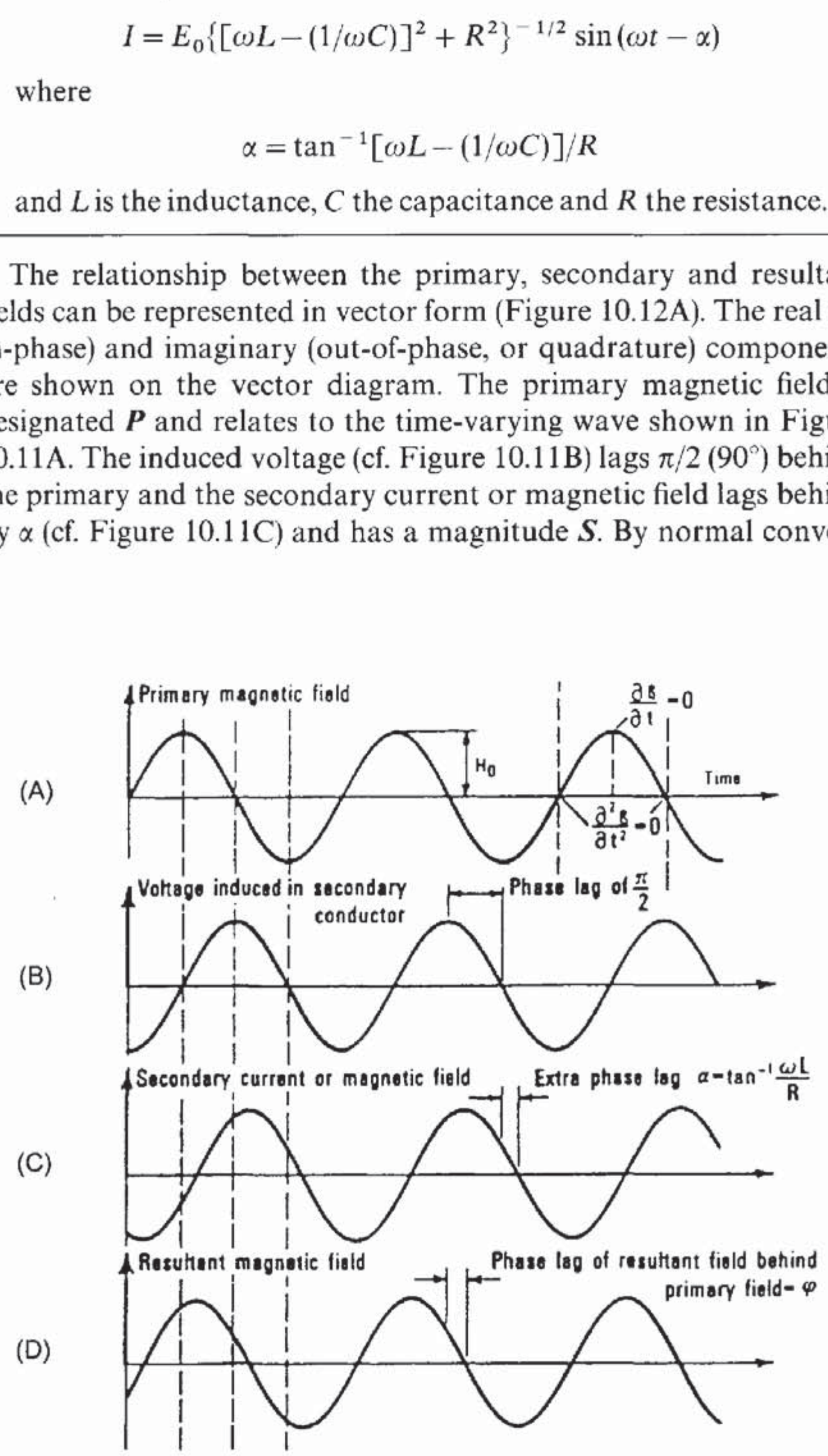

Figure 10.11 Relationships between induced voltages and associated phase lags between primary, secondary and resultant magnetic fields. Reproduced with permission from Beck (1981).

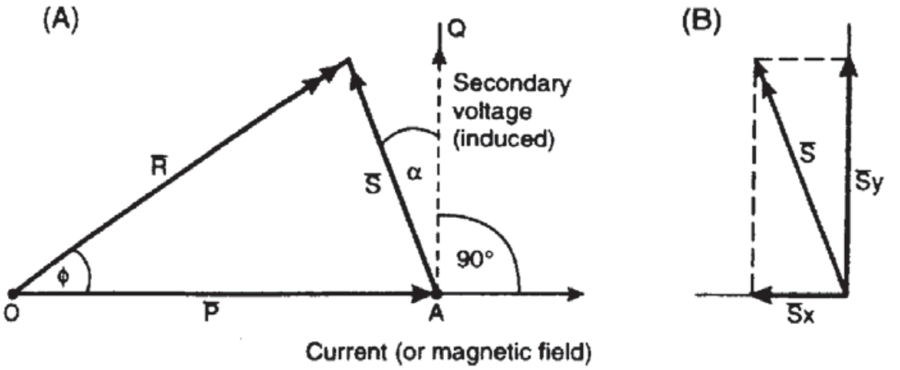

Figure 10.12 (A) Vector diagram defining the magnitudes and phase relationships of the primary and secondary fields. (B) The vectorial components of the secondary field in terms of the secondary voltage (Sy) and the current or primary magnetic field (Sx).

tions of vector diagrams, by completing the vector parallelogram, the resultant $\boldsymbol{R}$ of the primary and secondary fields (Figure 10.12A) is then defined with a total phase lag of ϕ (cf. Figure 10.11D). The secondary field $\boldsymbol{S}$ can be defined by the vectorial summation of its vertical and horizontal constituents (Figure 10.12B). Depending upon which equipment system is used, a number of these components can be measured from which an indication of the electrical properties of the sub-surface materials can be obtained.

10.2.2 Polarisation

It is important to consider two vectors $\boldsymbol{P}$ and $\boldsymbol{S}$ which differ in space by a spatial angle β (Figure 10.13A) and in phase by a phase angle ϕ. In order to calculate the resultant of these two vectors, it is necessary to resolve each into its horizontal and vertical components, denoted by suffices x and y, respectively. The mathematical summation is given in Box 10.2. The consequence of this summation process is that the resultant $\boldsymbol{R}$ always exists but varies continuously in magnitude and rotates in space. The tip of the resultant vector describes an ellipse in space, known as the 'ellipse of polarisation' (Figure 10.13C) which is inclined at an angle θ to the horizontal. The angle θ is known as the tilt or dip angle. Several EM methods (VLF and AFMAG) exploit this parameter and are known consequently as tilt-angle methods.

There are several special cases which should be mentioned. When the angle $\delta = 0$, equation (3) in Box 10.2 reverts to the equation of a straight line. This indicates that $\boldsymbol{R}$ is then a simple alternating vector and that the radiation comprises plane polarised waves. When $\delta = \pi/2$, the ellipse of polarisation is orientated such that axes are coincident with the x- and y-axes. The tilt angle θ becomes either zero or $n\pi/2$ when $\boldsymbol{P}$ and $\boldsymbol{S}$ are at right-angles and $\phi = \pi/2$. A further special case is when $\delta = \pi/2$ and $X = Y$, in which case equation (3) simplifies to the equation of a circle and the radiation is then circularly polarised.

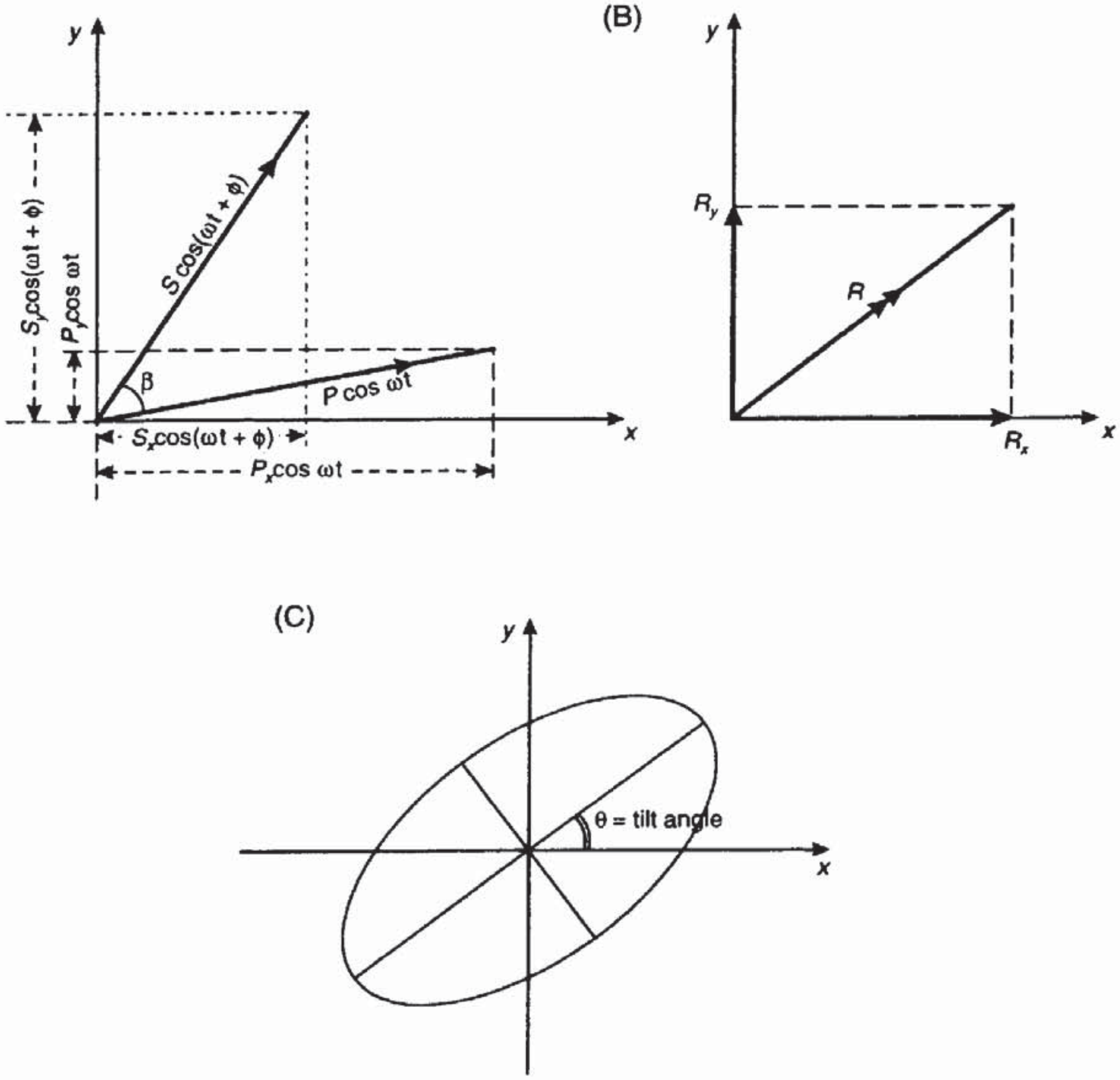

Figure 10.13 (A) Secondary field orientated in space at an angle β to the primary field. (B) The horizontal and vertical components R_x and R_y of the resultant of the summation of primary and secondary fields. (C) The ellipse of polarization inclined at the tilt-angle θ to the horizontal

Box 10.2 Polarisation ellipse

The primary field $\boldsymbol{P}(t)$ is given by:

$$\boldsymbol{P}(t) = \boldsymbol{P} \sin \omega t. \qquad (1)$$

The secondary field $\boldsymbol{S}(t)$ is given by:

$$\boldsymbol{S}(t) = \boldsymbol{S} \sin [\omega t - (\pi/2 + \phi)]. \qquad (2)$$

The resultant ($\boldsymbol{R}$) can be resolved into its horizontal and vertical components, suffices x and y respectively, where $\boldsymbol{R} = \boldsymbol{i}\boldsymbol{R}_x + \boldsymbol{j}\boldsymbol{R}_y$ and $R^2 = R_x^2 + R_y^2$:

$$R_x = P_x \cos \omega t + S_x \cos(\omega t + \phi) = X \cos(\omega t + \phi_1)$$

$$R_y = P_y \cos \omega t + S_y \cos(\omega t + \phi) = Y \cos(\omega t + \phi_2).$$

continued

continued

By solving the above equations and eliminating ωt, we obtain:

$$\frac{R_x^2}{X^2}+\frac{R_y^2}{Y^2}-\frac{2R_xR_y\cos\delta}{XY}=\sin^2\delta \tag{3}$$

where

$$\delta=\phi_2-\phi_1.$$

Equation (3) is the equation of an ellipse with its major axis inclined at an angle θ to the horizontal, where θ is defined by:

$$\tan 2\theta=\frac{XY\cos\delta}{X^2-Y^2}.$$

10.2.3 Depth of penetration of EM radiation

Of prime importance in EM surveying are a consideration of the depth of penetrating of the EM radiation and the resolution as a function of depth. In an isotropic resistive medium, EM waves would travel virtually indefinitely. However, in the real world, where surface conductivities are significant, the depth of penetration is often very limited. The depth of penetration is largely a function of frequency and the conductivity of the media present through which the EM radiation is to travel. At the usual frequencies (<5 kHz) used in EM exploration (excluding ground penetrating radar) attenuation effects are virtually negligible, but signal losses occur by diffusion.

A common guide to the depth of penetration is known as the *skin depth*, which is defined (Sheriff 1991) as the depth at which the amplitude of a plane wave has decreased to $1/e$ or 37% relative to its initial amplitude A_0. The mathematical definition of skin depth is given in Box 10.3. Given a known frequency for a particular equipment system, the unknown is the vertical variation of conductivity with depth. Different instrument manufacturers commonly cite effective depths of penetration for their instruments. For example, Geonics Ltd give the depth of penetration of their FEM systems (EM38/EM31/EM34) as a function of the inter-coil separation (see next chapter for details).

Box 10.3 Skin depth

Amplitude of EM radiation as a function of depth (z) relative to its original amplitude A_0 is given by:

$$A_z=A_0e^{-1}.$$

The skin depth δ (in metres) is given by:

$$\delta=(2/\omega\sigma\mu)^{1/2}=503(f\sigma)^{1/2}$$

where $\omega=2\pi f$, and f is the frequency in Hz, σ is the conductivity in S/m, and μ is the magnetic permeability (usually ≈ 1). A realistic estimate of the depth to which a conductor would give rise to a detectable EM anomaly is $\approx\delta/5$.

10.3 AIRBORNE EM SURVEYING

10.3.1 Background

The earliest known airborne EM (AEM) system was developed by Hans Lundberg in 1946 and first used in eastern Canada. It consisted of two coils mounted inside the cabin of a helicopter which had to fly at only 5 m above the ground if any conductors were to be detected!

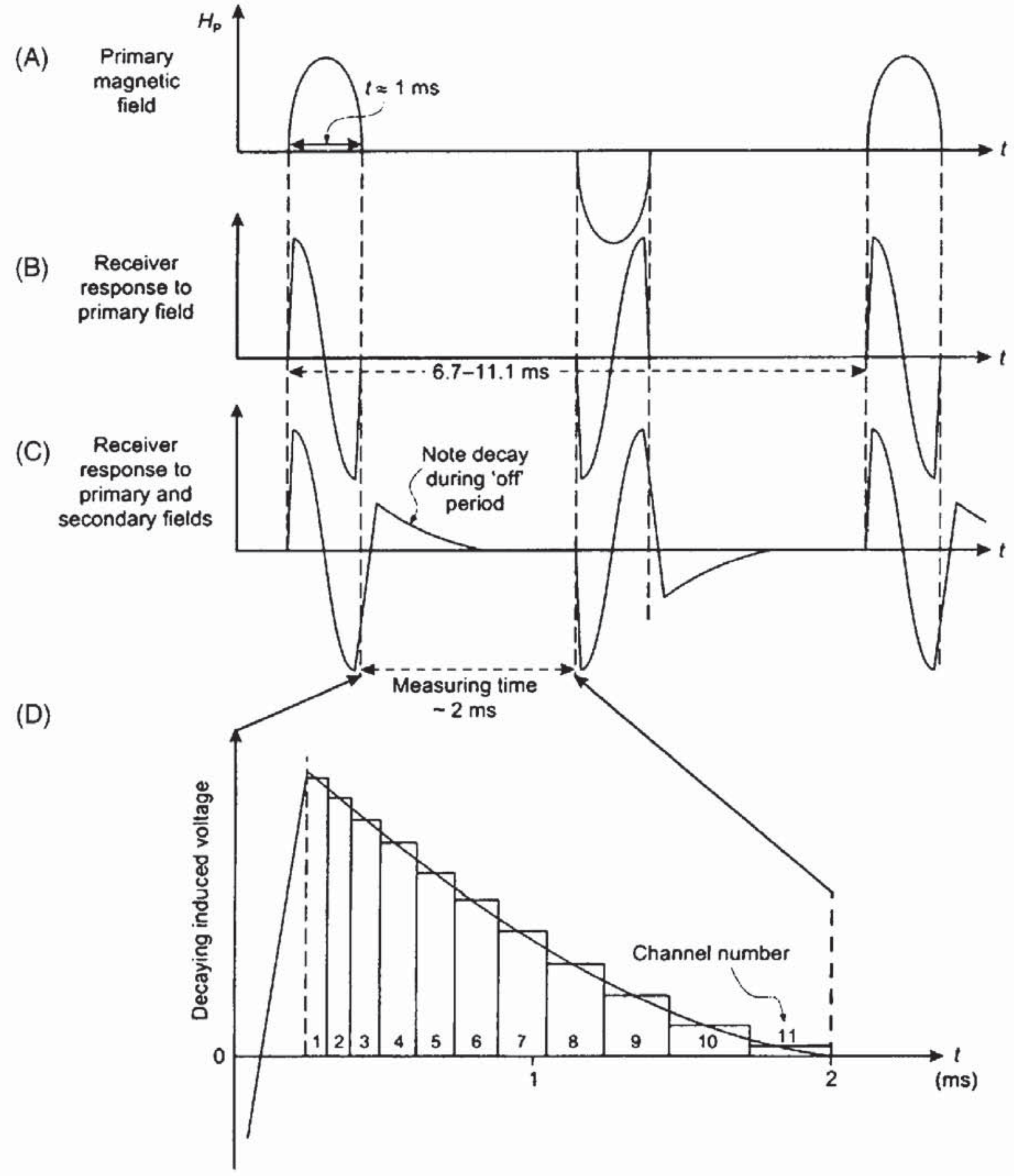

Figure 10.14 Input TEM system for airborne EM. (A) A primary magnetic field is generated that excites a receiver response (B). The measured response of the receiver is modified by an element (C) that is function of the ground properties. The decay curve (D) is sampled at designated time intervals (channels).

A detailed history of the development of airborne EM has been given by Pemberton (1962), Collett (1986), Becker *et al.* (1990), Palacky (1986) and Palacky and West (1991).

Following on from the early enthusiasm for AEM in the search for strategic base metals (such as copper, lead, zinc and nickel), many other airborne systems were developed. The most successful system was that developed in the late 1950s (Barringer 1962) and known as the INPUT system (INduced PUlse Transient), the principle of operation of which is shown in Figure 10.14. INPUT was developed further in the late 1970s to obtain greater depth penetration required in exploration for uranium and is now operated under the names QUESTEM (operated by Questor Surveys) and GEOTEM (Geoterrex Ltd). Further improvements to these systems were made in the mid-1980s with more powerful transmitters and modern computer technology. At this time an additional system known as PROSPECT became available along with its South African equivalent SPECTRUM; of the INPUT style AEM systems, only SPECTRUM, GEOTEM and QUESTEM are currently operational.

In the late 1970s, two clear styles of instrumentation deployment emerged, high-resolution helicopter surveying using towed instrument sondes and, particularly for deep penetration work, fixed-wing systems using rigid booms fitted to wingtips, mounted above the fuselage or on the nose and tail of the aircraft (Figure 10.15).

Applications of AEM surveying (excluding ground penetrating radar) to other than base metal exploration began in the 1960s with groundwater investigations, and later spread in the 1970s to include other forms of geological mapping, exploration for kimberlites in South Africa, and in the 1980s, mapping of Quaternary deposits in France, coal and lignite prospecting, detection of palaeochannels and salinity mapping in Australia, and shallow-water bathymetry and sea-ice thickness determinations in the USA. Further details of the range of applications of AEM can be found in the symposia edited by Palacky (1986) and Fitterman (1990), for example. Ground penetrating radar in the form of radio echosounding has been used from aircraft in polar regions to investigate major ice sheets since the late 1950s (see also Chapter 12). It is increasingly being used over glaciers at lower latitudes (e.g. Kennett *et al.* 1993).

10.3.2 AEM systems

The general principle of airborne EM surveying is shown in Figure 10.16. A powerful transmitter is mounted on the aircraft to generate the primary field in active systems, with a receiver either towed below in an instrument pod known as a 'bird' or on a separate part of the aircraft. The most commonly used systems are deployed from helicopters as they can be operated most easily at low flying heights and are much more manoeuvrable than fixed-wing aircraft.

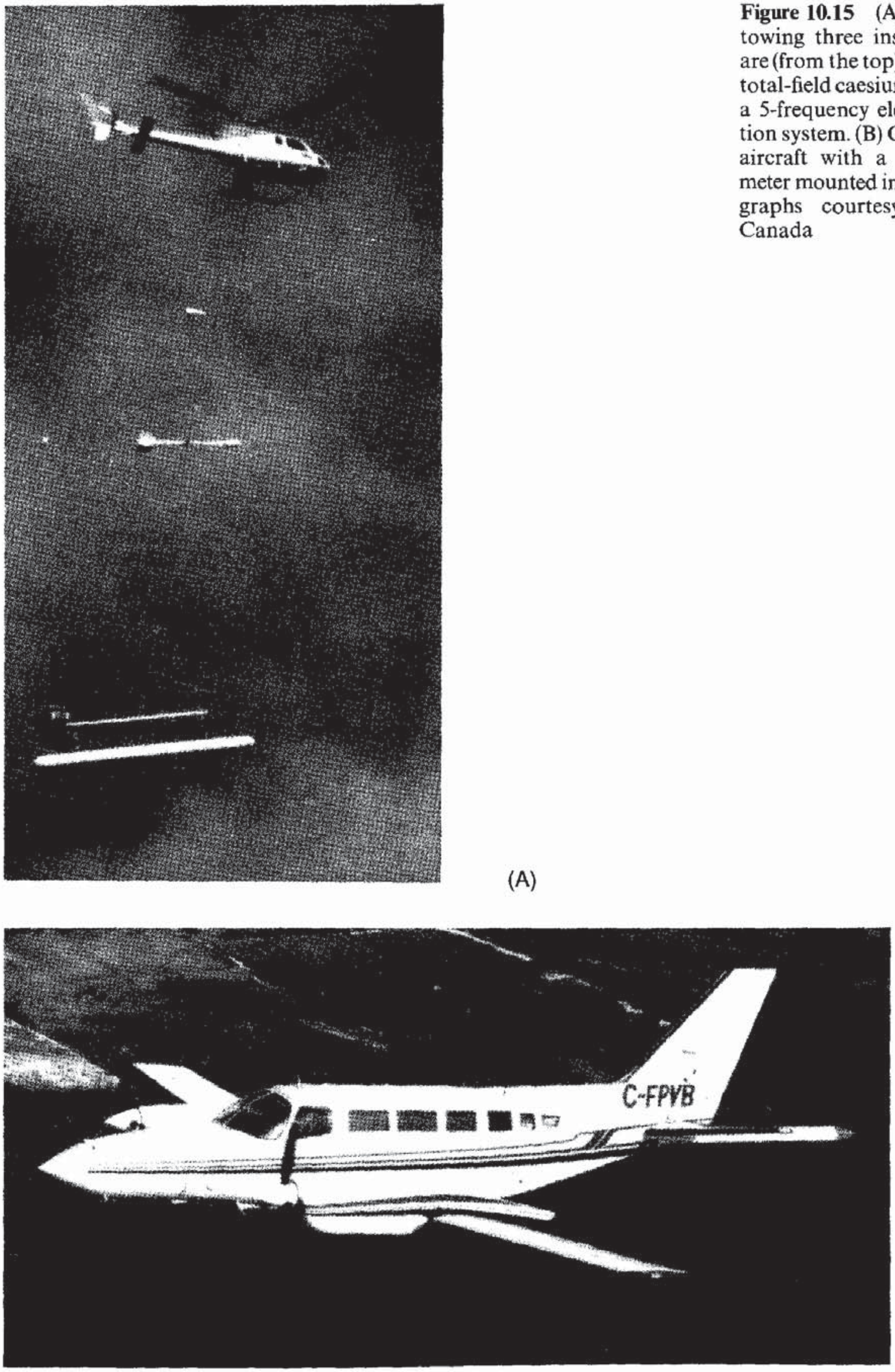

Figure 10.15 (A) Eurocopter AS350B towing three instrument pods. They are (from the top) 2-channel VLF-EM, total-field caesium magnetometer, and a 5-frequency electromagnetic induction system. (B) Cessna 404 fixed-wing aircraft with a total-field magnetometer mounted in a tail stringer. Photographs courtesy of Aerodat Inc., Canada

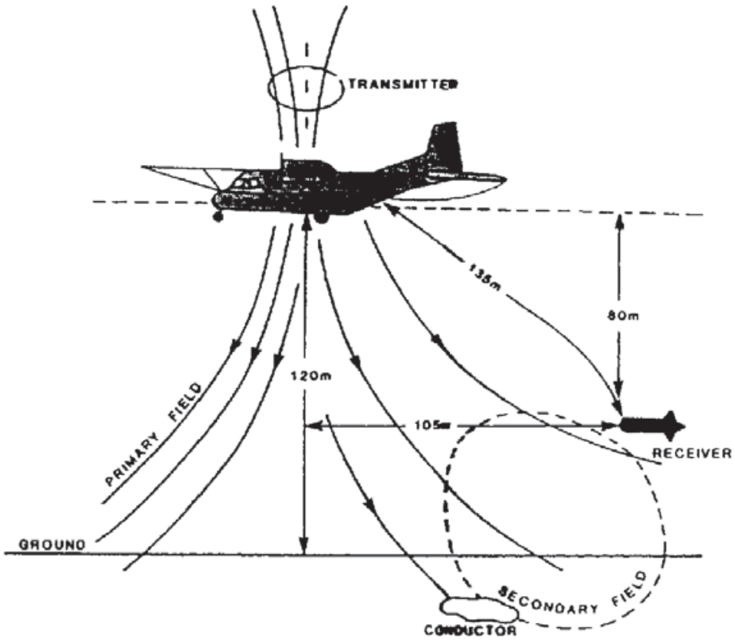

Figure 10.16 Principle of airborne electromagnetic surveying. The system shown deployed is of the towed-bird type. Reproduced with permission from Palacky and West (1991)

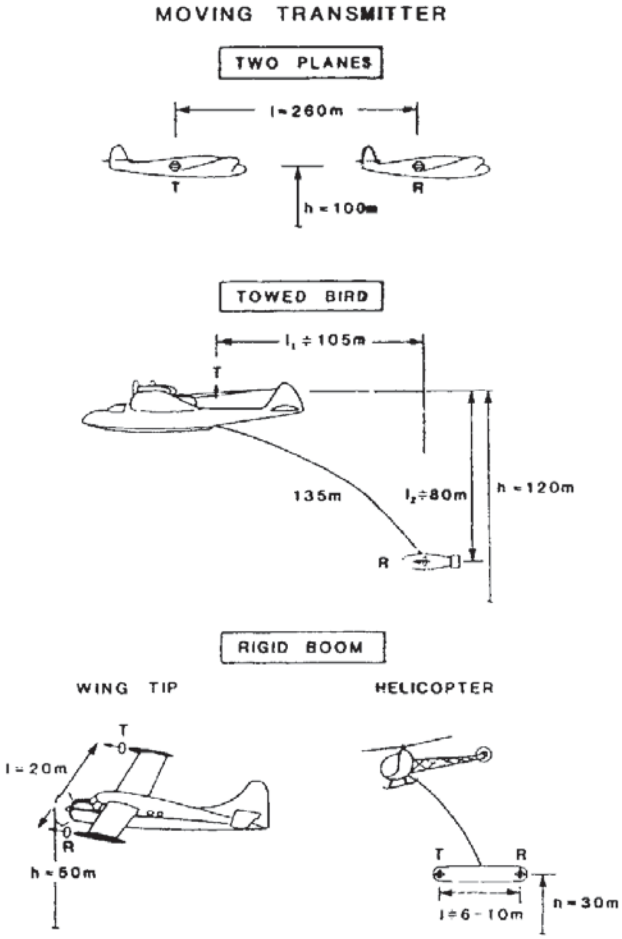

Figure 10.17 Transmitter–receiver geometry of five basic styles of active airborne EM systems. Reproduced with permission from Palacky and West (1991)

The various configurations of deployment of AEM systems are shown in Figure 10.17. There are two main types of transmitter–receiver geometries, towed bird and rigid boom systems. In some helicopter arrangements, the transmitter and receiver are both mounted in an instrument pod which is suspended below the aircraft. Further details of AEM systems have been given by Palacky and West (1991).

10.4 SEABORNE EM SURVEYING

10.4.1 Background

The principal difference between airborne and seaborne EM applications is largely one of scale. Whereas airborne surveys may involve flying heights of typically several tens to hundreds of metres, with transmitter–receiver distances of the order of 20–135 m, seaborne systems may have separations of tens of kilometres. Marine deployment of EM systems is usually for large-scale, crustal investigations and requires specialised instrument packages (Chave *et al.* 1991). There are a few examples of where land-based EM systems, such as a Geonics EM34, have been deployed in rubber inflatable boats and towed over shallow freshwater lakes and rivers in engineering investigations.

The main methods that have been adapted for use in the marine environment are magneto-telluric, magnetometric resistivity, and frequency- and time-domain systems. They have been reviewed in detail by Filloux (1987) and Chave *et al.* (1991).

The critical factor in all marine EM sounding is that the seawater is extremely conductive, and much more conductive than the geological materials at or below the seafloor. Seawater conductivity is strongly dependent upon salinity and temperature. The uppermost sediments under the ocean are usually water-saturated and have conductivities of the order of 0.1–1 S/m. This value decreases with increasing lithification and diagenesis which reduce the *in situ* porosity. Basaltic crust and upper mantle peridotite have conductivities ranging from 0.1 S/m at the base of the overlying sediments to three orders of magnitude less at a depth of about 10 km.

10.4.2 Details of marine EM systems

10.4.2.1 Magneto-telluric (MT) methods

All oceanic MT work has been specifically to probe the deep lithosphere and asthenosphere to obtain a vertical EM structural model to depths of hundreds of kilometres. The MT method is currently the only geophysical method capable of obtaining information about the electrical properties at depths greater than 30 km.

The only commercially available instruments for the measurements of a magnetic field are fluxgate magnetic sensors, with sensitivities of the order of 0.5–1 nT. These sensors are deployed directly on the seabed.

There are two types of device for the measurement of the electric component: (a) long-wire units, and (b) short-arm salt bridges. The long-wire system comprises an insulated wire typically 500 m to 1000 m long with Ag–AgCl electrodes connected to the ends of the wire and to a recording unit (Webb *et al.* 1985). The short-arm bridge apparatus utilises electrodes with spacings of only a few metres and salt bridges. Each salt bridge consists of a hollow tube attached to an Ag–AgCl electrode at one end and open to the sea at the other. The entire electrical unit has four arms (salt bridges and electrodes) which are spread out in the form of a horizontal cross which sits on top of a vertical cylinder housing the recording instruments. The base of this cylinder is located on a detachable tripod which, when lowered to the seafloor, is placed in contact with the seabed. Once measurements have been completed, the instrument module with salt bridges is released from the tripod and rises to the sea surface under slight positive buoyancy for subsequent recovery.

10.4.2.2 Magnetometric resistivity (MMR)

The marine version of MMR developed by Edwards *et al.* (1985), known as MOSES (Magnetometric Off-Shore Electrical Sounding), has been used for deep crustal sounding, mapping sulphide deposits near mid-ocean ridges (Wolfgram *et al.* 1986) and in the study of submarine permafrost below the Beaufort Sea. The general scheme of the MOSES method is shown in Figure 10.18.

The transmitter comprises a vertical long-wire bipole which extends from the sea surface to the seabed. A commutated current is fed

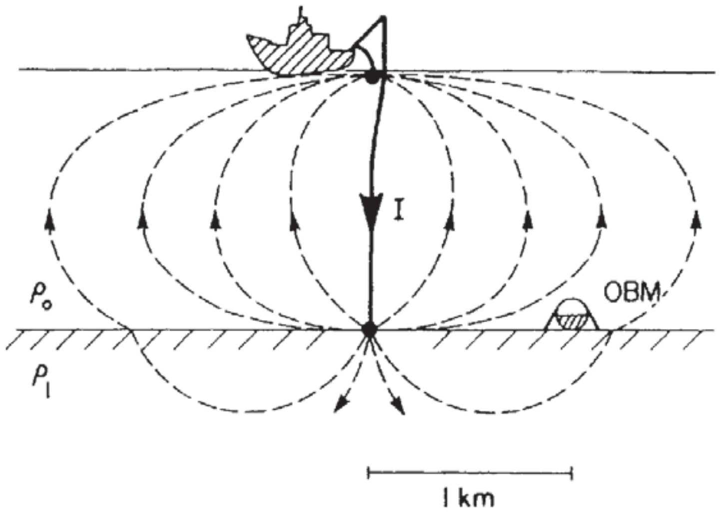

Figure 10.18 Schematic to illustrate the principle of the MOSES method. Current is passed via two electrodes, one at the sea surface and the other on the seafloor. The relatively small amount of current that enters into the resistive crust is proportional to the ratio of the conductivity of the crust to that of seawater. Only this small current contributes to the aximuthal magnetic field measured at a point on the seabed. OBM = ocean bottom monitor. Reproduced with permission from Chave *et al.* (1991).

to two large electrodes at each end of the vertical wire. The return electrical current passes through the seawater and the near-surface materials of the seafloor. A remote receiver located on the seafloor consists of two orthogonal horizontal component fluxgate magnetometers. Two orthogonal components of the magnetic field are measured as a function of frequency and source–receiver distance. The remote receiver consists of a concrete anchor shaped like an inverted cone into which a spherical instrument housing is located. The magnetometers are located within the detachable pressure case which can be released remotely from the concrete anchor for subsequent recovery.

A variation of the above system, called ICE-MOSES, was developed by Edwards *et al.* (1988) for use through sea ice. The sensor design is quite different from the original MOSES version. The sensor is deployed folded (and subsequently recovered) through a 25 cm diameter hole cut in the sea ice. Once through the hole, the unit unfolds to form a horizontal square which is lowered to the seabed. Along two sides at right-angles to each other are located the sensors which consist of coils wound on soft iron laminated cores and housed in stainless steel jackets.

ICE-MOSES is particularly important as it can be used to help define the physical properties of seafloor sediments to a depth of several hundreds of metres. Of particular interest in the Beaufort Sea, where ICE-MOSES was first used, is a seismically important permafrost layer between 100 and 600 m thick under seawater 10–100 m deep. This permafrost horizon is of importance for two reasons. First, a detailed knowledge of this layer is essential if reflection surveys undertaken in the same areas are to be interpreted accurately. Secondly, pockets of gas hydrate can be contained within the permafrost and these can be a possible resource as well as a hazard to drilling to deeper targets.

10.4.2.3 Controlled-source EM methods

Controlled-source EM systems use time-varying electric and magnetic dipole sources of known geometry to induce electric currents in the various conducting media present. The electric or magnetic character of the induced currents can be determined, from which estimates of the vertical electric conductivity structure of the geological materials present can be made. There are four basic source–receiver types but many combinations. The four are: *vertical and horizontal electric dipoles* (VED and HED) and *vertical and horizontal magnetic dipoles* (VMD and HMD).

In contrast to the land-based equivalent, marine controlled-source EM systems have both the source and receiver immersed in a conducting medium, and the electrical structure in both the seawater and the sub-seafloor materials affect the total induction achieved and thus

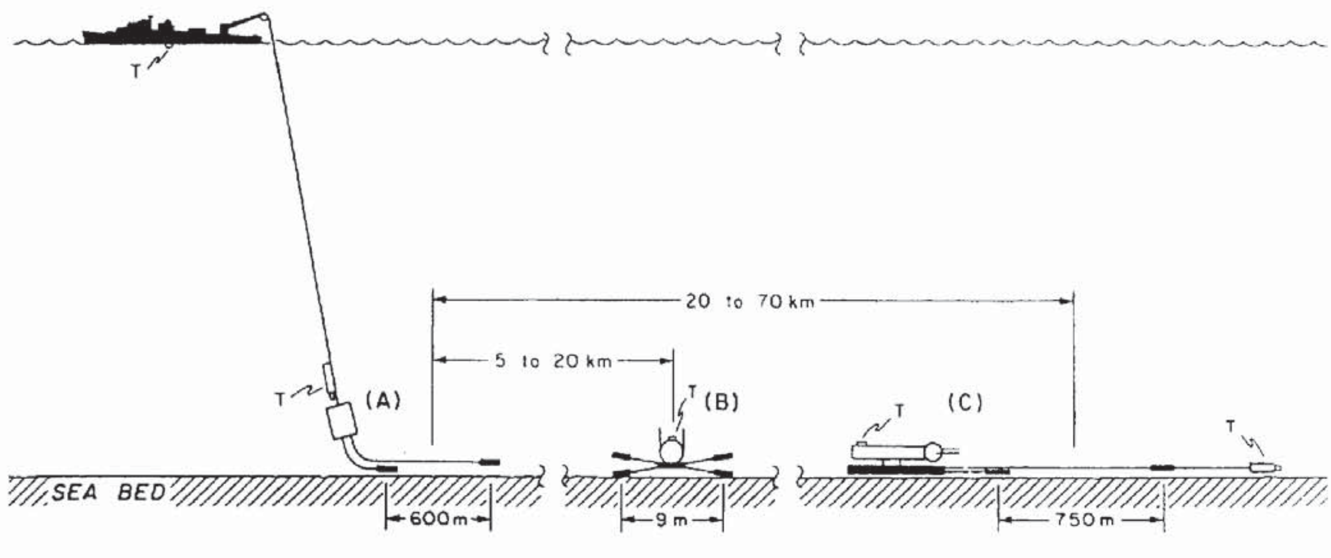

Figure 10.19 Typical layout for a horizontal electric dipole (HED) deep-sounding experiment. Power is supplied from a surface source (e.g. ship) to the seafloor transmitter (A) through a single conductor with a seawater return. The transmitter comprises an insulated antenna (with bare ends) of about 600 m length. Receivers are placed at ranges from 5 to over 70 km from the transmitter. Receivers may by either (B) an electric-field recorder (ELF) with a pair of rigid, orthogonal antennae of 9 m span, or (C) a long-antenna EM recorder (LEM), where the potential is measured between the ends of a 200–300 m insulated copper wire. Acoustics transponders (T) are used to locate all the seafloor components from a surface vessel. Reproduced with permission from Chave *et al.* (1991)

have to be taken into account in the interpretative modelling. In cases involving shallow water, for example over continental shelves, the position of the air/sea surface interface also has to be taken into consideration.

Three systems, two frequency-domain and one time-domain, will be described briefly to illustrate the diversity of systems currently being developed. The first is a submarine horizontal electric dipole (HED) frequency-domain system produced by Scripps Institution of Oceanography for deep sounding of the oceanic lithosphere. The source is a long (0.5–1 km) insulated cable terminating in stainless steel electrodes 15 m long. Receivers to detect the horizontal electric field are placed on the seabed between 1 and 200 km from the source. There are two types of electric receivers (Figure 10.19):

- The ELectric Field (ELF) free-fall recorder consists of a pair of rigid orthogonal antennae, each 9 m long, to the ends of which Ag–AgCl electrodes are fixed. ELF receivers are deployed between 5 km and 20 km from the transmitter.
- The Long antenna EM recorder (LEM) consists of 200–3000 m long insulated copper wire terminated by 0.5 m long Ag–AgCl electrodes. LEM recorders are placed up to 100 km or more away from the source.

The second basic system is also frequency-domain and is produced by Scripps for use over shallow continental shelves (Figure 10.20). The transmitter is made up of two 7 m long copper tubes 7 cm in diameter connected by 50 m of cable and powered directly by the survey vessel. The receiver array comprises a string of Ag–AgCl electrodes along a cable several hundred metres in length, all of which is in contact with the seabed. At the front end of the receiver array is a recording

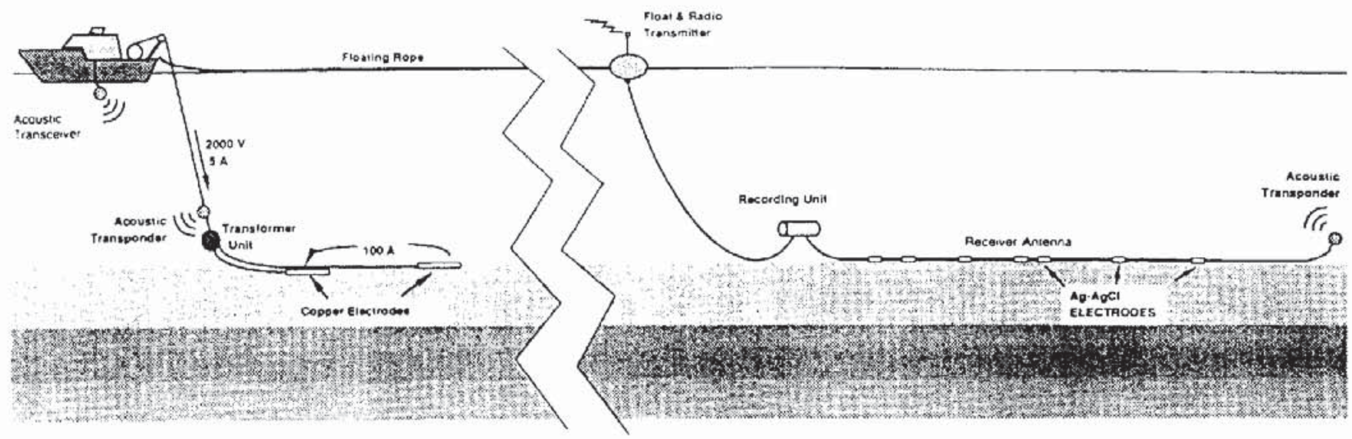

Figure 10.20 (*top*) Schematic to illustrate the components of a towed frequency-domain profiling system. The source antenna is towed immediately behind a research ship and is powered by the ship's generators. The receiving antenna is towed further behind from a radio-equipped buoy and consists of an array of Ag–AgCl electrodes. Acoustic transponders are used for location purposes. Reproduced with permission from Chave *et al.* (1991)

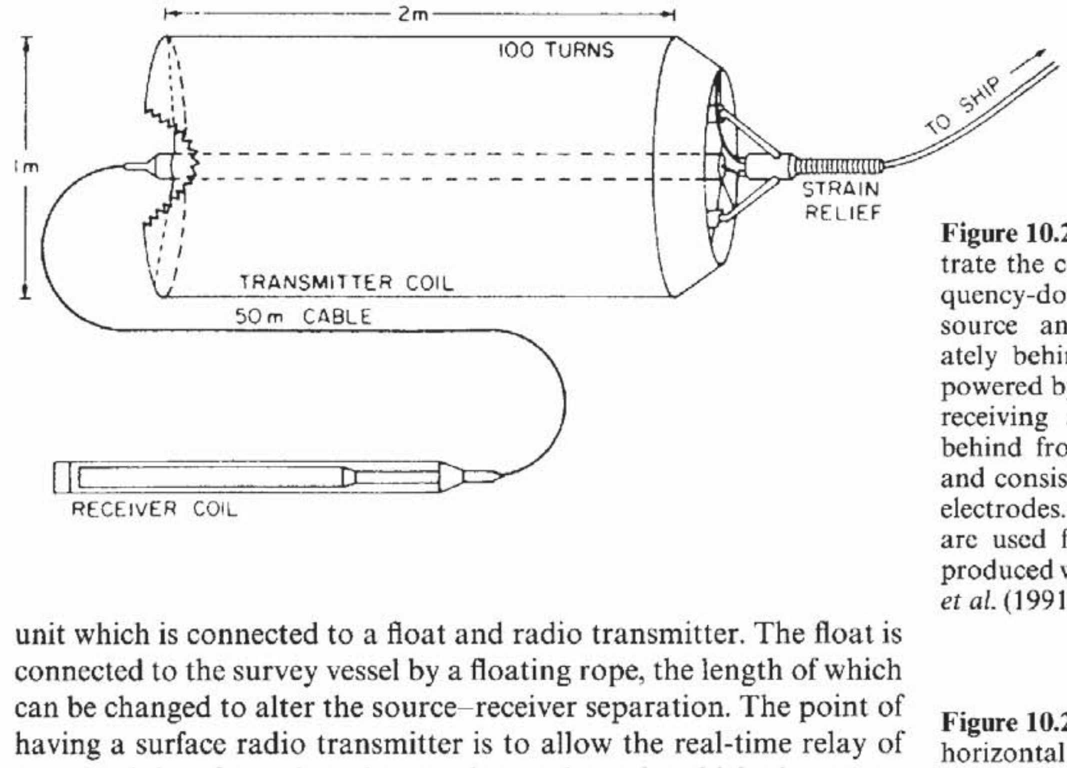

Figure 10.21 (*left*) Schematic of a horizontal magnetic dipole (HMD) transmitter that is connected to a surface vessel by an electric cable. The receiver is made up of a coil wound on an iron core and is encased in a protective plastic sleeve, all of which is streamed 50 m behind the transmitter. Reproduced with permission from Chave *et al.* (1991)

unit which is connected to a float and radio transmitter. The float is connected to the survey vessel by a floating rope, the length of which can be changed to alter the source–receiver separation. The point of having a surface radio transmitter is to allow the real-time relay of measured data from the submerged recorder unit, which also stores the data on to tape, directly to the survey vessel.

The third, time-domain, horizontal magnetic dipole (HMD) system (Figure 10.21) has been constructed by the University of Toronto, Canada. The transmitter comprises a 2 m long, 1 m diameter fibreglass cylinder in which 100 turns of wire are evenly embedded. Current is supplied to the transmitter from two car batteries located on the survey vessel. The polarity of the current is reversed every 5 ms to provide the transient EM signal. The receiver, which is made up of a modified iron core coil encased in a polycarbonate tube, is towed 50 m behind the transmitter. The entire source–receiver array is placed on to the seabed and is stationary during each measurement, which takes 90 s. The survey vessel is able to maintain headway by paying out additional cable during measurement periods and reeling in the extra cable between survey points. An advantage of this system is that the field source–receiver array is relatively small with a consequential improvement in the ease of deployment over some of the larger, and more unwieldy, frequency-domain systems. For any of these systems to become operational commercially, ease of operation is a major factor to be considered.

10.5 BOREHOLE EM SURVEYING

Whereas surface and airborne EM systems have regular geometries of sources and receivers, the addition of the third dimension via a borehole leads to an increased number of possibilities with associated complexities in interpretation. Borehole EM surveying differs from inductive well logging, which is used predominantly within the hydrocarbon industry, by virtue of the ability of being able to detect a conductive body at a significant distance away from the borehole. An induction logging device senses only those features through which the borehole has actually passed or within the near-field around the borehole (Figure 10.22).

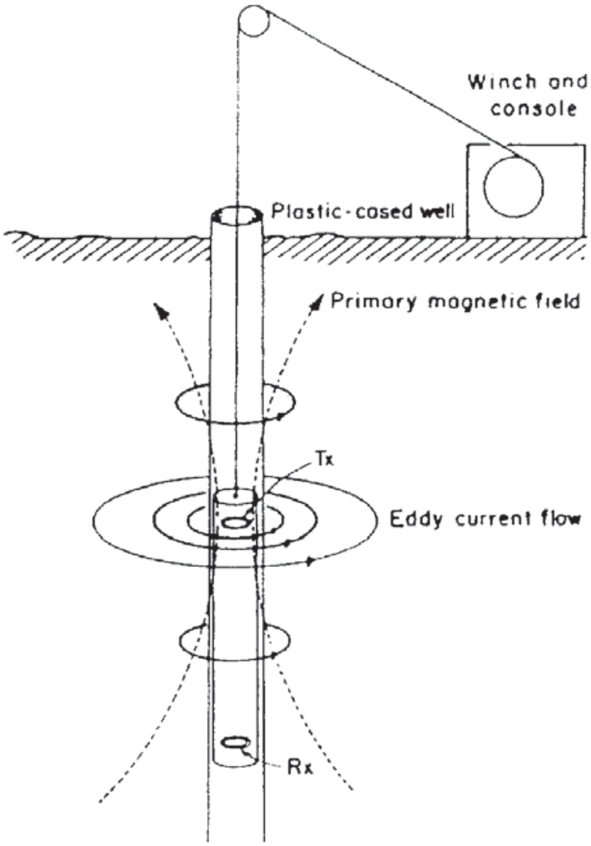

Figure 10.22 The basic principle behind an electromagnetic induction logger for use in boreholes. Reproduced with permission from McNeill (1990)

The principle of operation is the same as for ground conductivity meters. The system is able to measure the conductivity of the materials outside of a plastic cased borehole or well with diameters in the range 5–20 cm. The measurements are insensitive to the usually much more conductive borehole fluid within the casing (McNeill *et al.* 1988). Eddy currents are induced concentrically around the borehole using an intercoil separation of 0.5 m. This configuration provides a reasonable vertical resolution while at the same time maintains an adequate radial range of investigation (McNeill 1990). Drill-hole EM methods have been reviewed by Dyck (1991), and more details can be found therein.

There are three types of system in borehole surveying: dipole–dipole EM, rotatable-transmitter EM, and large-loop EM (LLEM) methods, of which the last is the most commonly used in mineral prospecting. The basic transmitter–receiver geometries are shown in Figure 10.23.

The dipole-dipole system has two coaxial coils separated by fibreglass rods with the transmitter preceding the receiver down the drill hole. Measurement points are taken as being the midpoint between transmitter and receiver. In-phase and quadrature components of the secondary magnetic field are measured as a percentage of the primary field. As the downhole system is deployed on a series of rods, the method can be used in near-horizontal and upwardly inclined holes,

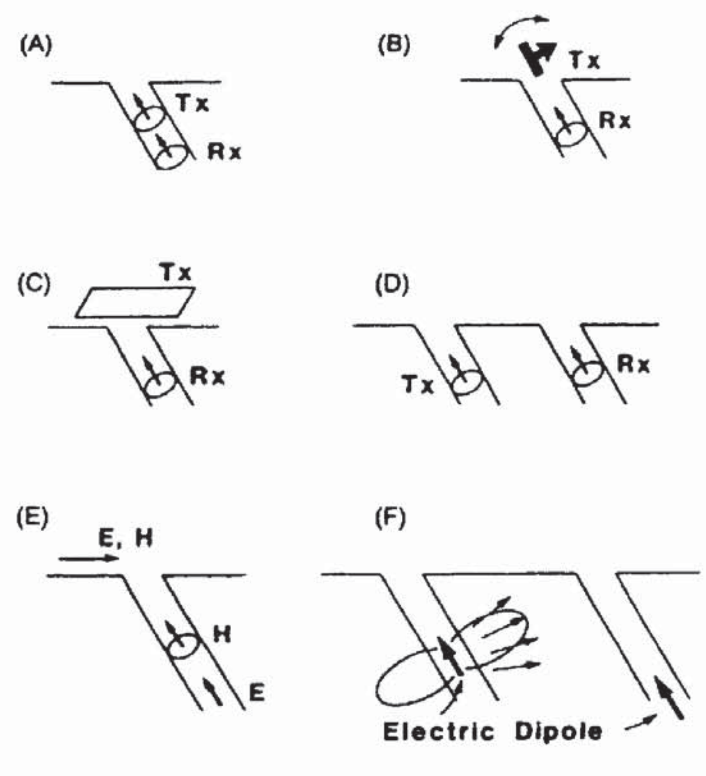

Figure 10.23 Drill-hole EM systems. (A) Dipole–Dipole EM. (B) Rotatable transmitter EM (with transmitter Tx shown side-on). (C) Large-loop EM. (D) Hole–hole dipole EM (variation of (A)). (E) remote transmitter (e.g. VLF radio source) for downhole measurement of electric and/or magnetic field. (F) Hole–hole wave propagation. Reproduced with permission from Dyck (1991)

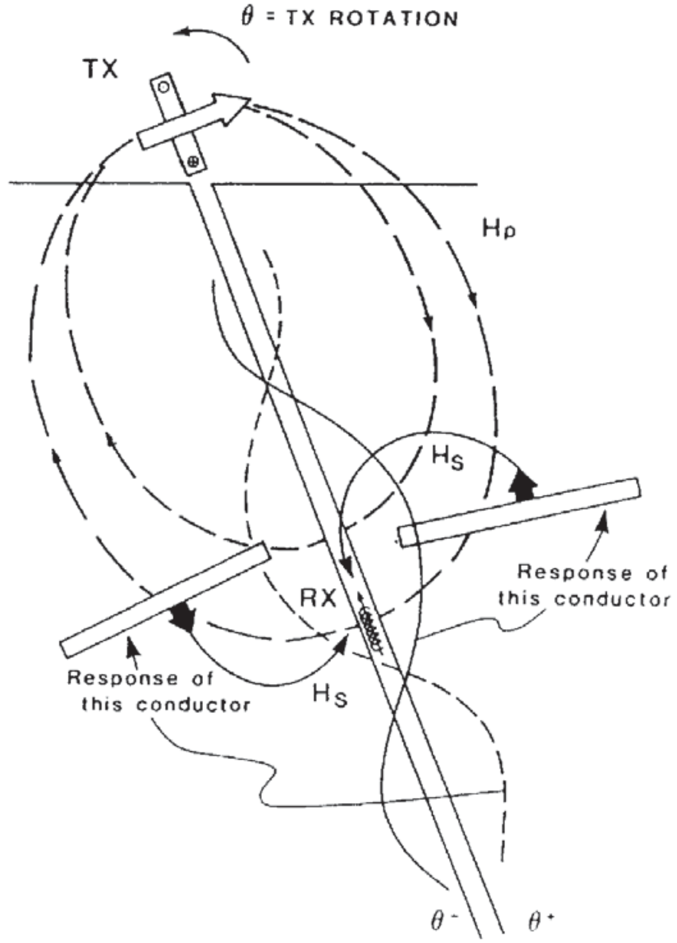

Figure 10.24 Magnetic fields produced by a rotatable transmitter and target conductor. The transmitter coil is rotated about an axis perpendicular to the plane of the diagram. The conductor to the right of the drill hole produces a negative (i.e. downward) component of secondary field H_s at the receiver position shown. A counterclockwise ($+\theta$) rotation of the transmitter is required to achieve a null by offsetting H_s with a component of H_p, assuming negligible change in transmitter–conductor coupling as the transmitter is tilted. Reproduced with permission from Dyck (1991)

and is then limited only by the ability to move the probes within the hole.

The rotatable-transmitter system is a version of the dipole–dipole method, but the transmitter remains at the drill hole collar throughout the survey while the receiver is moved up and down the hole (Figure 10.24). The receiver probe is moved down the hole in discrete intervals of several metres at a time. At each measurement point, the surface transmitter coil is rotated until a null point in the sensor is reached and the corresponding angle of tilt is recorded. The method is analogous to the surface tilt-angle technique.

The general layout for borehole LLEM surveying is shown in Figure 10.25. A loop transmitter is deployed at the ground surface adjacent to the borehole down which a detector is run to obtain a profile. Typical ground loop dimensions range from 100 m to 1000 m and are comparable to the depth of the drill hole being investigated. One ground loop, in conjunction with profiles down a number of drill holes from the surface and from within a mine gallery, are sufficient to resolve a sub-surface conducting target

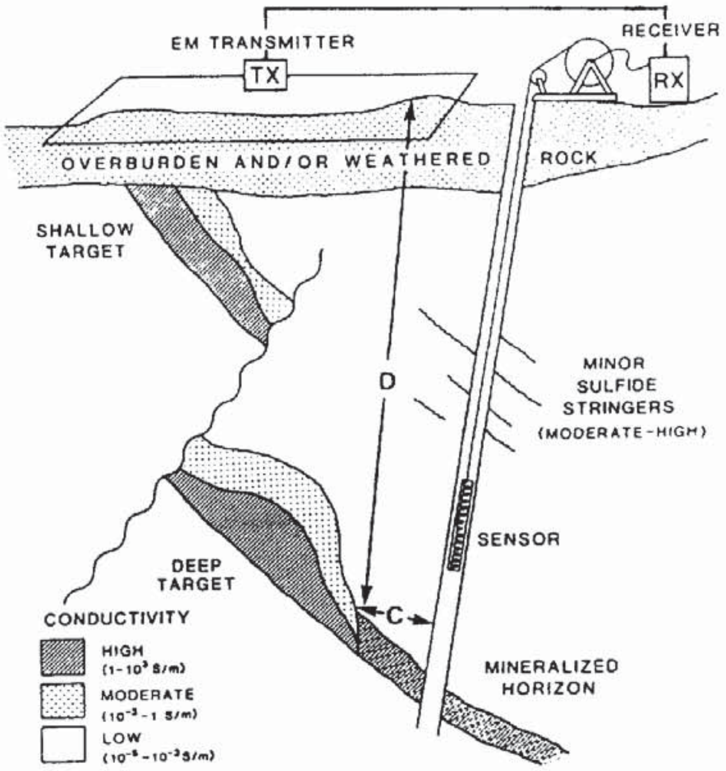

Figure 10.25 Schematic to illustrate the use of the large-loop drill-hole EM method for massive sulphide exploration in highly resistive environments such as Precambrian rocks. The system comprises a transmitter (Tx), a re-Clearance (*C*) is the critical distance in a drill-hole exploration problem involving a highly conductive target buried at depth *D*. There may be other bodies that are also conductive. Reproduced with permission from Dyck (1991)

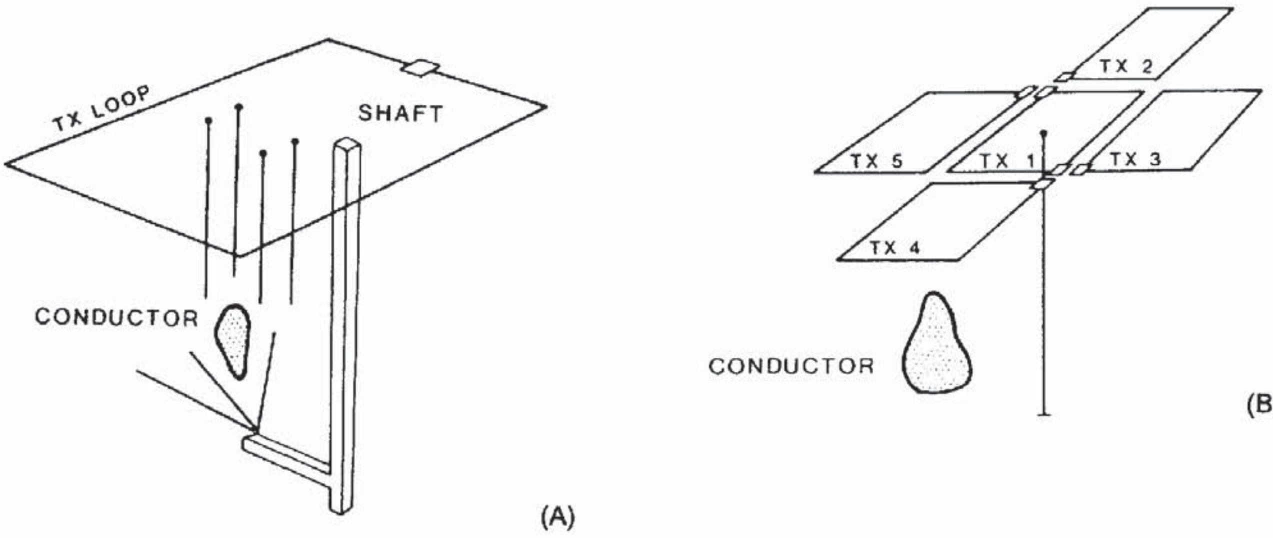

Figure 10.26 Transmitter layouts for surveying (A) a group of drill holes collared underground; and (B) a single isolated drill hole. Tx 1–5 are successive locations of the transmitter loop. Reproduced with permission from Crone (1986).

(Figure 10.26A). In contrast, if only one drill hole is available, one loop on its own does not provide azimuthal information necessary to locate the target. Consequently, a number of loop positions located around a collared borehole (Figure 10.26B) can be used to provide the additional information required.

There are three types of LLEM system depending upon the received primary waveform of system function, namely impulse-type, step-function type (both of which are TEM systems), and multi-frequency (FEM) type. Further details of these systems are given by Dyck (1991). Other systems that are available include down-hole VLF, and inter-hole wave propagation (e.g. Newman 1994) which can include borehole tomographic techniques (see also 'borehole radar tomography' in Chapter 12). Three component (magnetic field) systems are currently under development, although one prototype has been successfully deployed by Boliden Mineral AB, in Sweden (Pantze *et al.* 1986). A 1 × 1 km ground loop was used in an FEM system which operated at two frequencies, 200 Hz and 2000 Hz. Three sensors were mounted in a 32 mm diameter probe with the y-axis always being horizontal, x parallel to the long axis of the probe, and z always at right-angles to x and y. In-phase residuals (computed after the removal of the primary field and the background response caused by the host rock) were plotted as a function of profile distance along the drill hole. The shape and size of the excursion of each component away from a normal value provided information about the location (depth and azimuth) of a sub-surface conductive target.