world provide an advance warning service to advise of the probability of magnetic storm activity. In severe storms, all magnetic surveying has to stop as it is not practicable to correct for such extreme fluctuations. In minor disturbances, if a continuous-reading base station magnetometer is used, the diurnal variations can be corrected. In aeromagnetic surveys, it is necessary to specify contractually what constitutes a magnetic storm. Survey data adversely affected by magnetic disturbances may have to be reflown and this obviously has cost implications. Practical details of how to correct for diurnal variations are given in Section 3.6.2.

3.5 MAGNETIC INSTRUMENTS

The earliest known device which responded to the Earth's magnetic field was a magnetised spoon used by Chinese geomancers (diviners) in the first century AD. Compass needles were introduced for navigation around the year 1000 in China and in Europe about 200 years later. The first accurate measurement of the inclination of the Earth's field was made at Radcliffe in London in 1576 by Robert Norman. He described his instruments and collected data in his book *The Newe Attractive* (1581), which was the first book ever to be devoted to geomagnetism.

Magnetometers used specifically in geophysical exploration can be classified into three groups: the torsion (and balance), fluxgate and resonance types, of which the last two have now completely superseded the first. Torsion magnetometers are still in use at 75% of geomagnetic observatories, particularly for the measurement of declination. Magnetometers measure horizontal and/or vertical components of the magnetic field (F_h and F_z respectively) or the total field $\boldsymbol{F}_t$ (see Figure 3.12).

3.5.1 Torsion and balance magnetometers

Historically the first to be devised (1640), these comprise in essence a magnetic needle suspended on a wire (torsion type) or balanced on a pivot. In the Earth's magnetic field the magnet adopts an equilibrium position. If the device is taken to another location where the Earth's magnetic field is different from that at the base station, or if the magnetic field changes at the base station, the magnet will align itself to the new field and the deflection from the rest position is taken as a measure of the Earth's magnetic field. The Swedish mine compass, Hotchkiss superdip, and Thalén-Tiberg magnetometer are all early examples of this type of device. In 1915, Adolf Schmidt devised his variometer in which a magnetic beam was asymmetrically balanced on an agate knife edge (Figure 3.17) and zeroed at a base station.

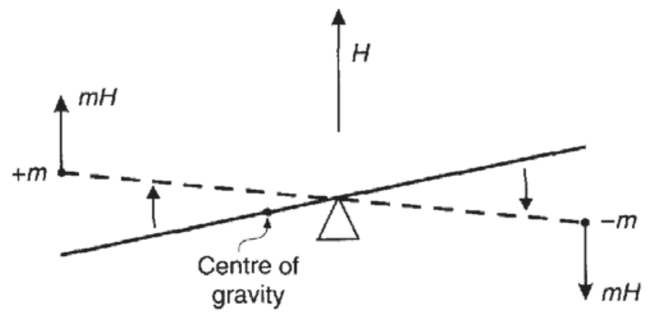

Figure 3.17 Basic principle of operation of a torsion or balance-type magnetometer

Deflections from the rest position at other locations were then read using a collimating telescope. To be used it had to be orientated at right-angles to the magnetic meridian so as to remove the horizontal component of the Earth's field. The device was calibrated using Helmholtz coils so that the magnitude of the deflection was a measure of the vertical component of the field strength.

A development of the Schmidt variometer was the compensation variometer. This measured the force required to restore the beam to the rest position. In exploration work, the greatest precision with a balance magnetometer was only 10 nT at best. For further details of these devices, see the descriptions by Telford *et al.* (1990).

3.5.2 Fluxgate magnetometers

The fluxgate magnetometer was developed during the Second World War to detect submarines. It consists of two parallel cores made out of high-permeability ferromagnetic material. Primary coils are wound around these cores in series but in opposite directions (Figure 3.18). Secondary coils are also wound around the cores but in the opposite sense to the respective primary coil. A current alternating at 50–

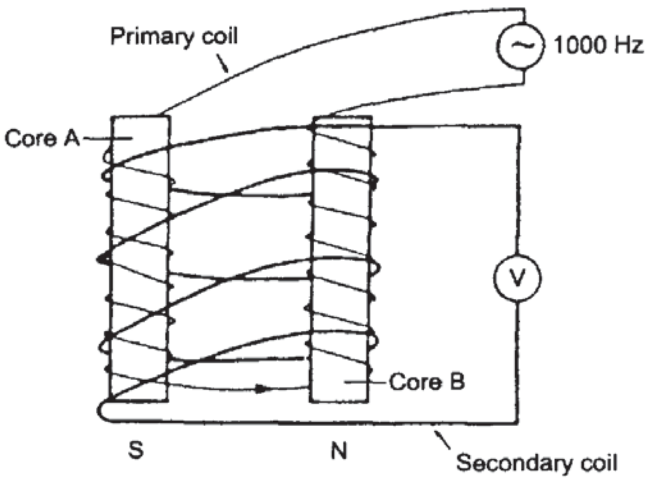

Figure 3.18 Basic operating principle of the fluxgate magnetometer

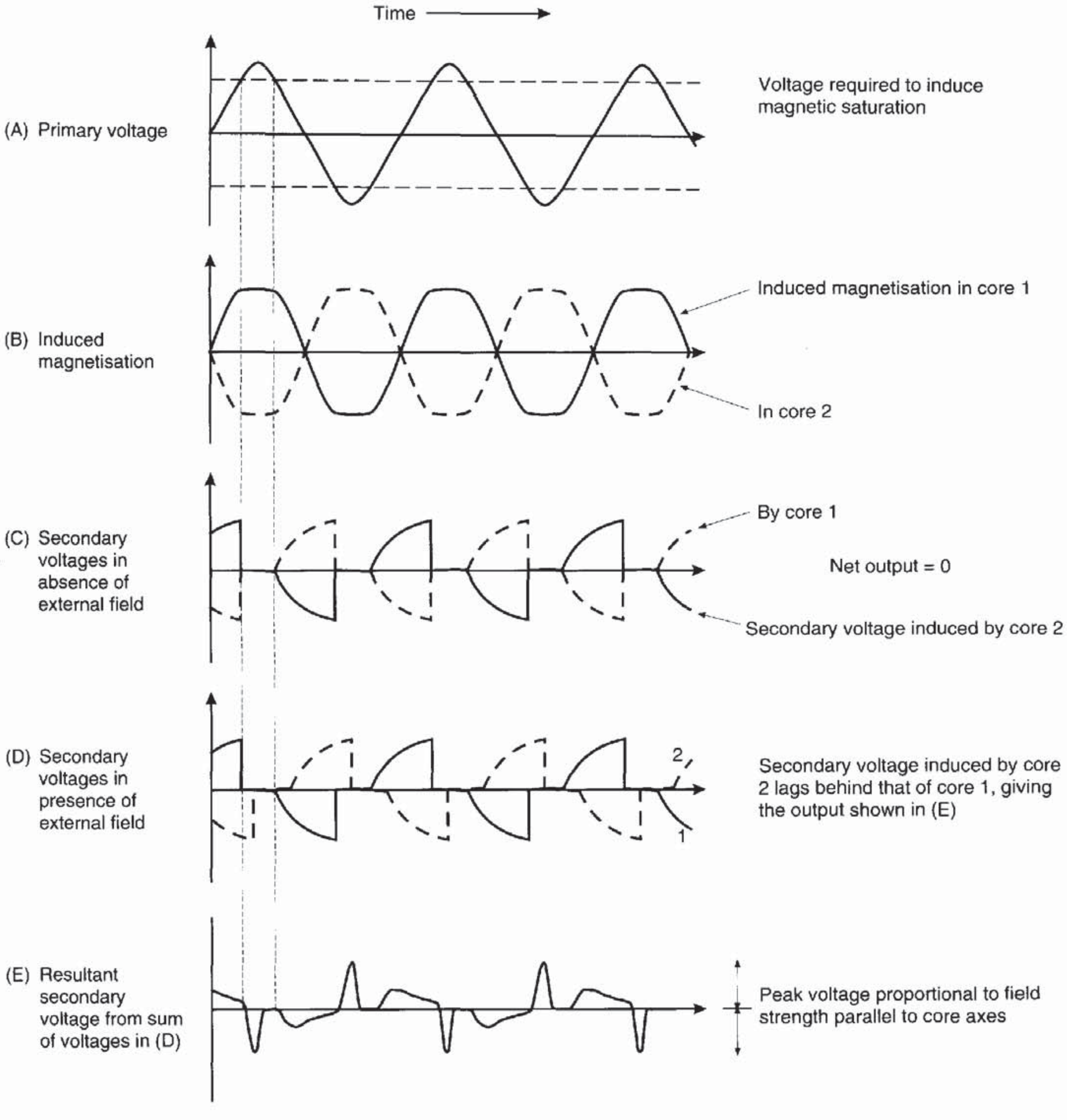

Figure 3.19 Response characteristics of primary and secondary circuits in a fluxgate magnetometer

1000 Hz (Figure 3.19A) is passed through the primary coils which drives each core through a B–H hysteresis loop (cf. Figure 3.6) to saturation at every half-cycle (Figure 3.19B) in the absence of an external field, so inducing a magnetic field in each core. The generated alternating magnetic field induces an in-phase voltage within the secondary coils. This voltage reaches its maximum when the rate of change of the magnetic field is fastest (Figure 3.19C). As the coils are wound in opposing directions around the two cores, the secondary voltages are in phase but have opposite polarity (Figure 3.19C) so that the sum of the two voltages is at all times zero. However, when the cores are placed in the Earth's magnetic field, a component of that field will be parallel to the orientation of the cores. Consequently, the core whose primary field is reinforced by the ambient external field will reach saturation earlier than the other core whose magnetic field is opposed by the external field. This has the effect of shifting the phases of the secondary voltages (Figure 3.19D) so that the sum of the two secondary voltages is now non-zero (Figure 3.19E). The peak amplitude of the pulsed output of the combined secondary coils is proportional to the magnitude of the external field component (Primdahl 1979).

The fluxgate magnetometer can be used to measure specific magnetic components with the same attitude as the sensor cores. As the fluxgate magnetometer is relatively insensitive to magnetic field gradients, it has the advantage that it can be used in areas where very steep gradients would militate against the use of resonance-type devices which are affected. Some portable fluxgate magnetometers suffer from temperature effects owing to inadequate thermal insulation, which can reduce the resolution to only ± 10 to 20 nT, this being inadequate for ground exploration surveys. They are used quite widely in airborne surveys where better thermal insulation can be ensured and additional devices can be used to aid the consistent orientation of the sensor cores. In such cases, an accuracy to within ± 1 nT can be achieved. In addition, fluxgate instruments can provide a continuous output which is another advantage for airborne applications. Fluxgate magnetometers can also be used in down-hole logging applications in mineral exploration.

3.5.3 Resonance magnetometers

There are two main types of resonance magnetometer: the *proton free-precession magnetometer*, which is the best known, and the *alkali vapour magnetometer*. Both types monitor the precession of atomic particles in an ambient magnetic field to provide an absolute measure of the total magnetic field, $\boldsymbol{F}$.

The proton magnetometer has a sensor which consists of a bottle containing a proton-rich liquid, usually water or kerosene, around which a coil is wrapped, connected to the measuring apparatus (Figure 3.20). Each proton has a magnetic moment $\boldsymbol{M}$ and, as it is always in motion, it also possesses an angular momentum $\boldsymbol{G}$, rather like a spinning top. In an ambient magnetic field such as the Earth's ($\boldsymbol{F}$), the majority of the protons align themselves parallel with this field with the remainder orientated antiparallel (Figure 3.21A). Consequently, the volume of proton-rich liquid

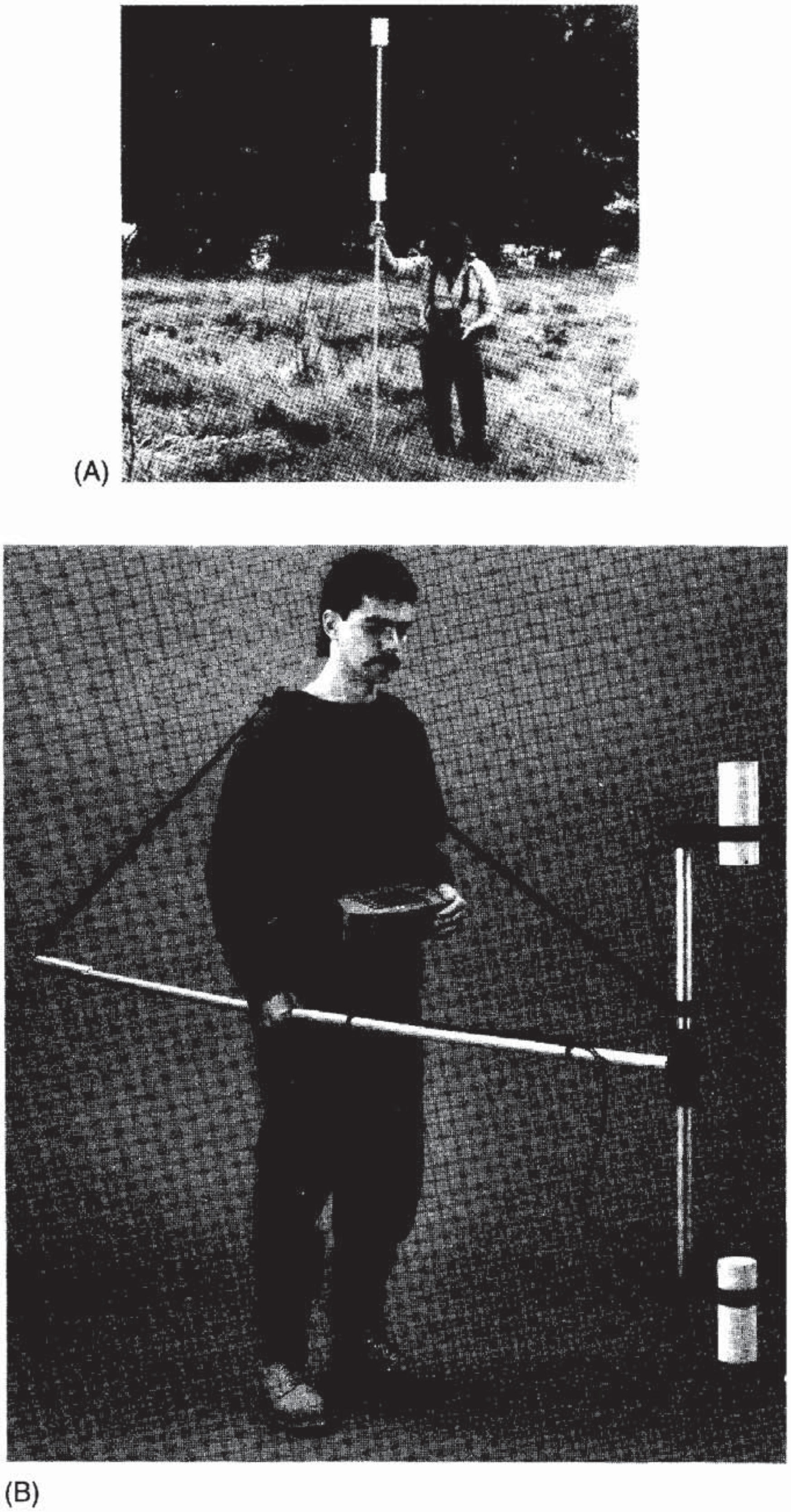

Figure 3.20 (A) A nuclear proton precession magnetometer in use, and (B) a caesium vapour magnetometer. Courtesy of Geometrics

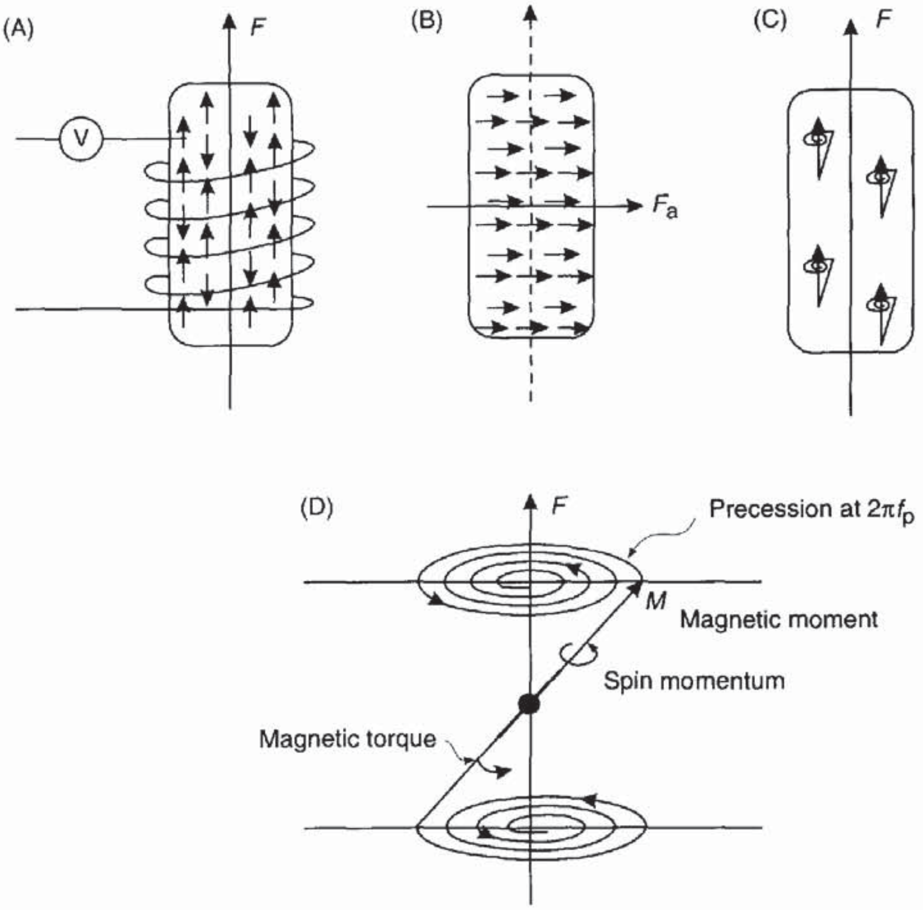

Figure 3.21 Basic operating principles of a proton magnetometer. After Kearey and Brooks (1991), by permission

acquires a net magnetic moment in the direction of the ambient field (***F***).

A current is applied to the coil surrounding the liquid, generating a magnetic field about 50 to 100 times stronger than, and at right-angles to, the Earth's field. The protons align themselves to the new magnetic direction (Figure 3.21B). When the applied field is switched off, the protons precess around the pre-existent ambient field ***F*** (Figure 3.21C) at the *Larmor precession frequency* (f_P) which is proportional to the magnetic field strength ***F*** (Box 3.6). As protons are charged particles, as they precess they induce an alternating voltage at the same frequency as f_P into the coil surrounding the sensor bottle. Interaction between adjacent protons causes the precession to decay within 2–3 seconds, which is sufficient time to measure the precession frequency. To obtain a value of ***F*** to within ±0.1 nT, frequency must be measured to within ±0.004 Hz, which is quite easily achieved. This resolution is equivalent to 1 part in 10^6, which is 100 times less sensitive than in gravity measurements.

Box 3.6 Magnetic field strength, F, and precession frequency, f_P

$$F = 2\pi f_P/\Phi_P$$

where Φ_P is the gyromagnetic ratio of the proton, which is the ratio of the magnetic moment and spin angular momentum (see Figure 3.21); and

$$\Phi_P = 0.26753\ \text{Hz/nT and } 2\pi/\Phi_P = 23.4859\ \text{nT/Hz}.$$

Thus:

$$F = 23.4859 f_P.$$

For example, for $F = 50\,000$ nT, $f_P = 2128.94$ Hz.

One of the limiting factors of the proton magnetometer is that its accuracy is reduced in areas of high magnetic gradient. As the sensor bottle is of the order of 15 cm long, a strong field gradient of 500 nT/m, for example, means that there is a 75 nT difference in field strength between the top and bottom of the sensor and the rate of damping is increased. The accuracy of measurement of the precession frequency is thus reduced. As a guide, if the gradient is 400 nT/m, the precision is at best 1 nT; for 200 nT/m it is 0.5 nT.

As the precession frequency is only a function of field strength, there is no need to orientate the field sensor. Modern proton magnetometers give a direct readout of the field strength in nanoteslas and data can be automatically output into a datalogger for subsequent downloading into a computer.

Proton magnetometers are used extensively not only in land surveys but also at sea and in airborne investigations. In marine surveys, the magnetometer sensor bottle, which is located in a sealed unit called a 'fish', is deployed two or three ship's lengths astern so as to be sufficiently removed from magnetic interference from the ship. In the case of aircraft, two techniques are used. One is to tow the sensor bottle at least 30 m below and behind the aircraft in what is called a 'bird', or place it in a non-magnetic boom called a 'stinger' on the nose, on the tail fin or on a wingtip of the aircraft. In the fixed mode, special magnetic compensation measures can be taken to annul the magnetisation of the aircraft; the excellence of the compensation is called the *figure of merit* (FOM) rating. The fitting of active compensation systems in modern aircraft has improved FOM values and reduced the time taken for compensation, and so helped to improve the cost-effectiveness of airborne surveys. In addition to ground, marine and airborne applications, proton magnetometers can be deployed down boreholes, and can be particularly useful in mineral exploration programmes.

A limitation on proton magnetometers, particularly in airborne surveys, is the rate at which measurements can be made. As the proton precession and measurement take a finite time (of the order of a second or longer), continuous readings are not possible and this can be restricting in some situations.

One manufacturer (GEM Systems Inc.) has produced a modified precession instrument that utilises the Overhauser Effect. An electron-rich fluid containing free radicals is added to a standard hydrogen-rich liquid. The combination increases the polarisation by a factor of 5000 in comparison with standard liquids. Overhauser proton precession uses a radio-frequency (RF) magnetic field and so needs only minimal power, in contrast with high-power direct current fields used in traditional proton precession magnetometers. Polarisation and magnetisation can occur simultaneously and thus rapid sampling of the total field strength (two readings per second) can be achieved.

The second type of resonance magnetometer is the *alkali vapour magnetometer* or *optical absorption magnetometer*, which utilises the optical pumping technique (Bloom 1962). The principle on which this method is based is illustrated in Figure 3.22. Under normal conditions of temperature and pressure, electrons exist at certain energy states (A and B) around the nucleus of the atom. According to quantum physics, it is only possible to transfer an electron from a lower energy state (A) to one with higher energy (B) in discrete jumps. If a vapour of an element such as rubidium or caesium is illuminated by a light whose filament is made of the same element, the light emitted is at the correct wavelength for incident photons to be absorbed by the vapour and the low-energy state electrons excited up to higher levels. If the incident light is circularly polarised, only electrons in the A_1 orbit will be excited or 'optically pumped' up to the B orbit. At this point, the excess photons will be transmitted through the excited vapour and will be detected by the photocell as an increase in light intensity.

A small alternating current is passed through a coil at a frequency of between 90 and 300 kHz to induce a magnetic field around the

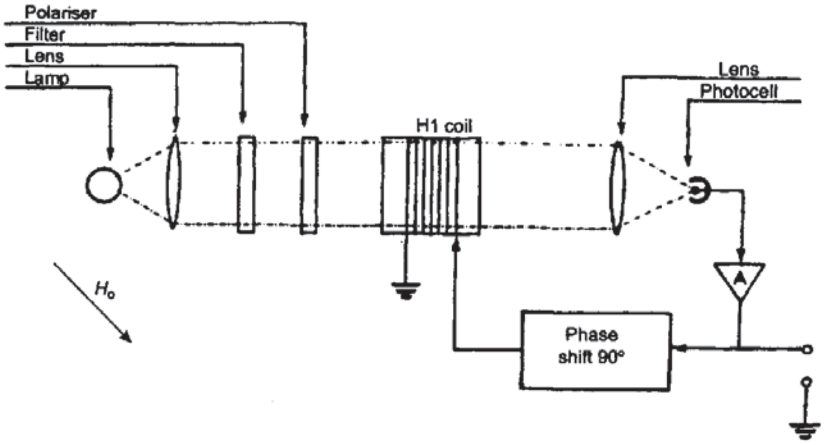

Figure 3.22 Optical pumping – principle of the alkali vapour magnetometer. From James (1990), by permission

alkali vapour cell. The frequency is tuned until it is locked into the Larmor frequency for the alkali vapour concerned. This small magnetic field energises some electrons back into their vacant A ground states. The consequence of this is that the light intensity at the photocell diminishes as photons are absorbed by the alkali vapour in the cell until saturation is reached again. Photons will continue to be absorbed until all the available electrons have been excited to the B state, when the light at the photocell will again be at its most intense. Consequently, the cycled optical pumping produces a light at the photocell that flickers at the Larmor precession frequency, which can easily be measured. As the precession frequency is dependent upon the ambient field strength of the Earth (see Box 3.6), the total field strength can be determined from a measurement of the precession frequency. The factor $2\pi/\Phi_p$ is approximately equal to 0.2141 and 0.1429 nT/Hz for rubidium and sodium respectively, which give corresponding precession frequencies of 233.5 and 350 kHz in a field of 50 000 nT. As long as the light beam axis is not parallel or antiparallel to the Earth's magnetic field (when no signals would be produced), the precession frequency can be measured with sufficient accuracy so that the magnetic field strength can be determined to within ± 0.01 nT. The measurement time is extremely small, and so alkali vapour magnetometers can be used as virtually continuous reading instruments, which makes them ideally suited to airborne surveys.

For land-based archaeological or environmental geophysical applications, self-oscillating split-beam caesium vapour magnetometers have been developed, largely from military ordnance detection instruments (e.g. the Geometrics G-822L magnetometer). Sampling rates of up to 10 readings per second are possible with a sensitivity of 0.1 nT.

3.5.4 Cryogenic (SQUID) magnetometers

The most sensitive magnetometer available is the cryogenic magnetometer which operates using processes associated with superconductivity, details of which have been given by Goree and Fuller (1976). These magnetometers are perhaps better known as *SQUID* (Superconducting QUantum Interference Device) magnetometers. Used extensively in palaeomagnetic laboratories, the SQUID magnetometer has also been developed for use in aeromagnetic surveying since the early 1980s, particularly as a gradiometer. SQUIDs can have a measurement sensitivity of 10^{-5} nT/m; this means that two sensors need only be placed 25 cm or less apart, thus making it possible to have the entire sensor system in a very small space. This has great advantages in mounting the equipment in aircraft, in borehole probes and in submarine devices where space is at a premium. Measurement accuracy of the total field strength is within ± 0.01 nT.

Technical difficulties over the use of liquid helium, which has to be maintained at a temperature of 4.2 K for superconductivity to occur, limit the widespread deployment of SQUID magnetometers. They are rarely, if ever, used in surface magnetic measurements.

3.5.5 Gradiometers

A gradiometer measures the difference in the total magnetic field strength between two identical magnetometers separated by a small distance. In airborne work, typical separations between sensors is 2 m to 5 m for stingers (Figure 3.23) and up to 30 m for birds. In ground instruments, a separation of 0.5 m is common. The magnetic field gradient is expressed in units of nT/m and taken to apply at the mid-point between the sensors. A major advantage of gradiometers is that because they take differential measurements, no correction for diurnal variation is necessary as both sensors will be equally affected. As gradiometers measure the vertical magnetic gradient, noise effects from long-wavelength features are suppressed and anomalies from shallow sources are emphasised. For detailed high-resolution surveys exploring for mineral targets, magnetic gradiometry is the preferred method (Hood 1981).

Fluxgate and resonance-type magnetometers are commonly used in ground surveys. Where continuous-reading devices are required, such as when automatic datalogging is being used, fluxgate gradiometers are preferable (e.g. Sowerbutts and Mason 1984). A detailed although dated comparison of the different types of gradiometers and magnetometers has been made by Hood *et al.* (1979).

Self-oscillating split-beam caesium vapour gradiometers have also been developed for small-scale land-based surveys, such as Geomet-

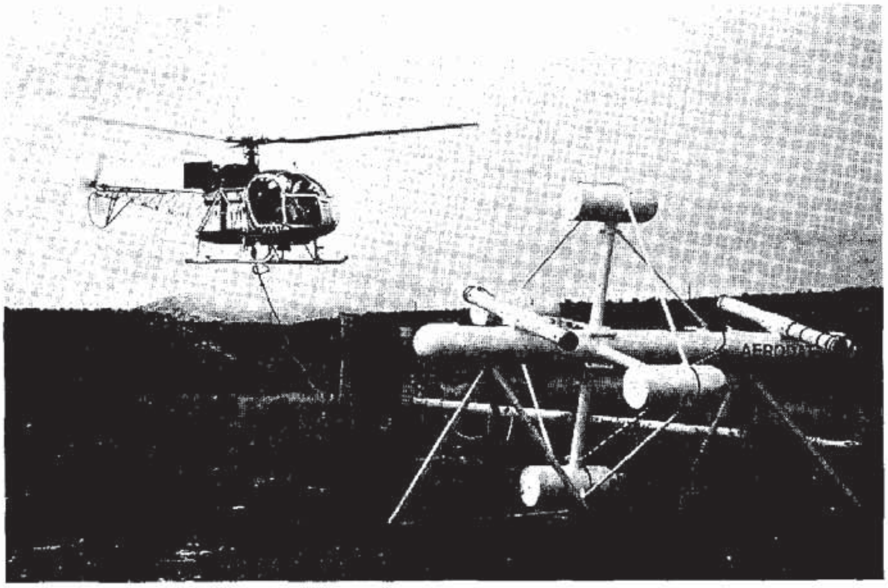

Figure 3.23 Eurocopter AS315 about to lift a 3-axis magnetic gradiometer system. Courtesy of Aerodat Inc., Canada