prepared sample (either a drill core or powdered rock in a tube) with that of a standard sample of magnetic material (often $FeCl_3$ powder in a test tube) when the sample is in the Gauss-A position [Eq. (3.15a)]. The susceptibility of the sample is found from the ratio of deflections:

$$k_s = k_{std} d_s / d_{std}$$

d_s and d_{std} are the deflections for the sample and standard, respectively. The samples must be of the same size.

A similar comparison method employs an inductance bridge (Hague, 1957) having several air-core coils of different cross sections to accommodate samples of different sizes. The sample is inserted into one of the coils and the bridge balance condition is compared with the bridge balance obtained when a standard sample is in the coil. The bridge may be calibrated to give susceptibility directly, in which case the sample need not have a particular geometry (although the calibration may not be valid for samples of highly irregular shape). This type of instrument with a large diameter coil is used in field measurements on outcrop. The bridge is balanced first with the coil remote from the outcrop and then lying on it. A calibration curve obtained with a standard relates k and the change in inductance.

(b) Measurement of remanent magnetism. Measurement of remanent susceptibilty is considerably more complicated than that of k. One method uses an astatic magnetometer, which consists of two magnets of equal moment that are rigidly mounted parallel to each other in the same horizontal plane with opposing poles. The magnetic system is suspended by a torsion fiber. The specimen is placed in various orientations below the astatic system and the angular deflections are measured. This device, in effect, measures the magnetic field gradient, so that extraneous fields must either be eliminated or made uniform over the region of the sample. Usually the entire assembly is mounted inside a three-component coil system that cancels the Earth's field.

Another instrument for the analysis of the residual component is the *spinner magnetometer*. The rock sample is rotated at high speed near a small pickup coil and its magnetic moment generates alternating current (ac) in the coil. The phase and intensity of the coil signal are compared with a reference signal generated by the rotating system. The total moment of the sample is obtained by rotating it about different axes.

Cryogenic instruments for determining two-axes remanent magnetism have been developed (Zimmerman and Campbell, 1975; Weinstock and Overton, 1981). They achieve great sensitivity because of the high magnetic moments and low noise obtainable at superconducting temperatures.

3.4. FIELD INSTRUMENTS FOR MAGNETIC MEASUREMENTS

3.4.1. General

Typical sensitivity required in ground magnetic instruments is between 1 and 10 nT in a total field rarely larger than 50,000 nT. Recent airborne applications, however, have led to the development of magnetometers with sensitivity of 0.001 nT. Some magnetometers measure the absolute field, although this is not a particular advantage in magnetic surveying.

The earliest devices used for magnetic exploration were modifications of the mariner's compass, such as the Swedish mining compass, which measured dip I and declination D. Instruments (such as *magnetic variometers*, which are essentially dip needles of high sensitivity) were developed to measure Z_e and H_e, but they are seldom used now. Only the modern instruments, the fluxgate, proton-precession, and optical-pump (usually rubidium-vapor) magnetometers, will be discussed. The latter two measure the absolute total field, and the fluxgate instrument also generally measures the total field.

3.4.2. Fluxgate Magnetometer

This device was originally developed during World War II as a submarine detector. Several designs have been used for recording diurnal variations in the Earth's field, for airborne geomagnetics, and as portable ground magnetometers.

The fluxgate detector consists essentially of a core of magnetic material, such as mu-metal, permalloy, or ferrite, that has a very high permeability at low magnetic fields. In the most common design, two cores are each wound with primary and secondary coils, the two assemblies being as nearly as possible identical and mounted parallel so that the windings are in opposition. The two primary windings are connected in series and energized by a low frequency (50 to 1,000 Hz) current produced by a constant current source. The maximum current is sufficient to magnetize the cores to saturation, in opposite polarity, twice each cycle. The secondary coils, which consist of many turns of fine wire, are connected to a *differential amplifier*, whose output is proportional to the difference between two input signals.

The effect of saturation in the fluxgate elements is illustrated in Figure 3.7. In the absence of an external magnetic field, the saturation of the cores is

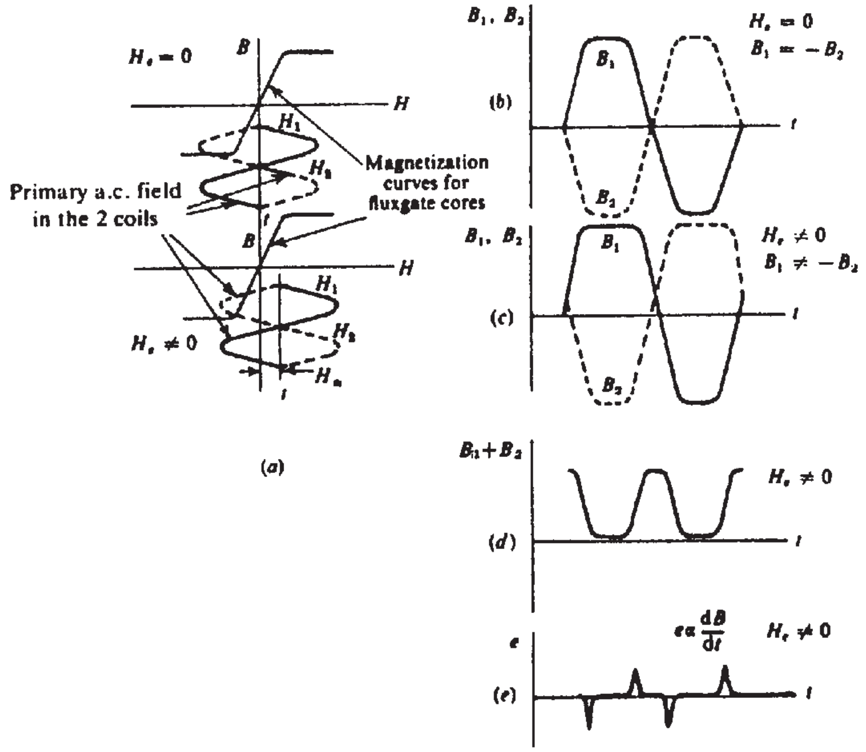

Figure 3.7. Principle of the fluxgate magnetometer. Note that $H_e = F_e$, *etc. (From Whitham, 1960.) (a) Magnetization of the cores. (b) Flux in the two cores for* $F_e = 0$. *(c) Flux in the two cores for* $F_e \neq 0$. *(d)* $F_1 + F_2$ *for* $F_e \neq 0$. *(e) Output voltage for* $F_e \neq 0$.

symmetrical and of opposite sign near the peak of each half-cycle so that the outputs from the two secondary windings cancel. The presence of an external field component parallel to the cores causes saturation to occur earlier for one half-cycle than the other, producing an unbalance. The difference between output voltages from the secondary windings is a series of voltage pulses which are fed into the amplifier, as shown in Figure 3.7d. The pulse height is proportional to the amplitude of the biasing field of the Earth. Obviously any component can be measured by suitable orientation of the cores.

The original problem with this type of magnetometer – a lack of sensitivity in the core – has been solved by the development and use of materials having sufficient initial permeability to saturate in small fields. Clearly the hysteresis loop should be as thin as possible. There remains a relatively high noise level, caused by hysteresis effects in the core. The fluxgate elements should be long and thin to reduce eddy currents. Improvements introduced to increase the signal-to-noise ratio include the following:

1. By deliberately unbalancing the two elements, voltage spikes are present with or without an ambient field. The presence of the Earth's field increases the voltage of one polarity more than the other and this difference is amplified.
2. Because the odd harmonics are canceled fairly

Figure 3.8. Portable fluxgate magnetometer.

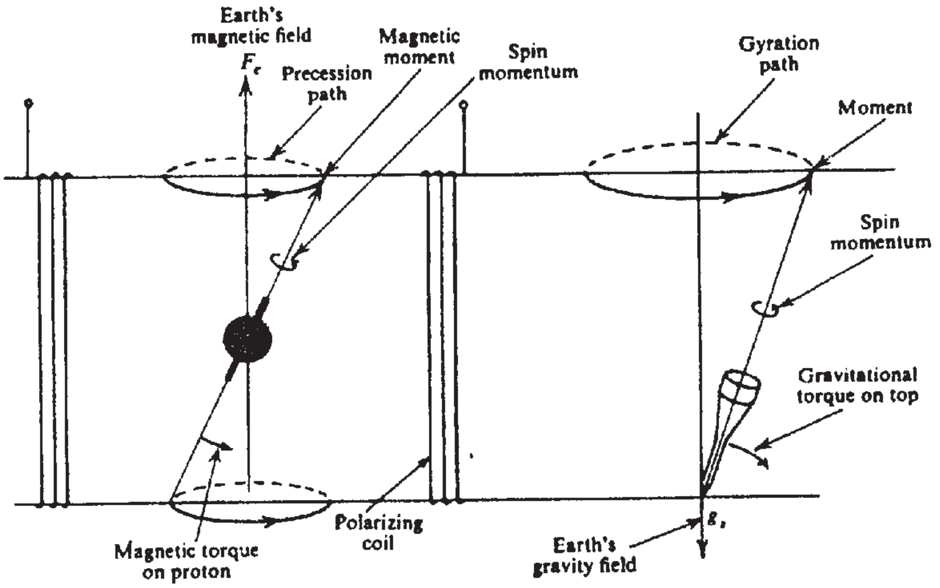

Figure 3.9. Proton precession and spinning-top analogy.

well in a reasonably matched set of cores, the even harmonics (generally only the second is significant) are amplified to appear as positive or negative signals, depending on the polarity of the Earth's field.

3. Most of the ambient field is canceled and variations in the remainder are detected with an extra secondary winding.
4. Negative feedback of the amplifier outputs is used to reduce the effect of the Earth's field.
5. By tuning the output of the secondary windings with a capacitance, the second harmonic is greatly increased; a phase-sensitive detector, rather than the difference amplifier, may be used with this arrangement.

There are several fundamental sources of error in the fluxgate instrument. These include inherent unbalance in the two cores, thermal and shock noise in cores, drift in biasing circuits, and temperature sensitivity (1 nT/°C or less). These disadvantages are minor, however, compared to the obvious advantages – direct readout, no azimuth orientation, rather coarse leveling requirements, light weight (2 to 3 kg), small size, and reasonable sensitivity. Another attractive feature is that any component of the magnetic field may be measured. No elaborate tripod is required and readings may be made very quickly, generally in about 15 s. A portable fluxgate instrument is shown in Figure 3.8.

3.4.3. Proton-Precession Magnetometer

This instrument grew out of the discovery, around 1945, of nuclear magnetic resonance. Some nuclei have a net magnetic moment that, coupled with their spin, causes them to precess about an axial magnetic field.

The proton-precession magnetometer depends on the measurement of the free-precession frequency of protons (hydrogen nuclei) that have been polarized in a direction approximately normal to the direction of the Earth's field. When the polarizing field is suddenly removed, the protons precess about the Earth's field like a spinning top; the Earth's field supplies the precessing force corresponding to that of gravity in the case of a top. The analogy is illustrated in Figure 3.9. The protons precess at an angular velocity ω, known as the *Larmor precession frequency*, which is proportional to the magnetic field F, so that

$$\omega = \gamma_p F \tag{3.30a}$$

The constant γ_p is the *gyromagnetic ratio of the proton*, the ratio of its magnetic moment to its spin angular momentum. The value of γ_p is known to an accuracy of 0.001%. Since precise frequency measurements are relatively easy, the magnetic field can be determined to the same accuracy. The proton, which is a moving charge, induces, in a coil surrounding the sample, a voltage that varies at the precession frequency ν. Thus we can determine the magnetic field from

$$F = 2\pi\nu/\gamma_p \tag{3.30b}$$

where the factor $2\pi/\gamma_p = 23.487 \pm 0.002$ nT/Hz. Only the total field may be measured.

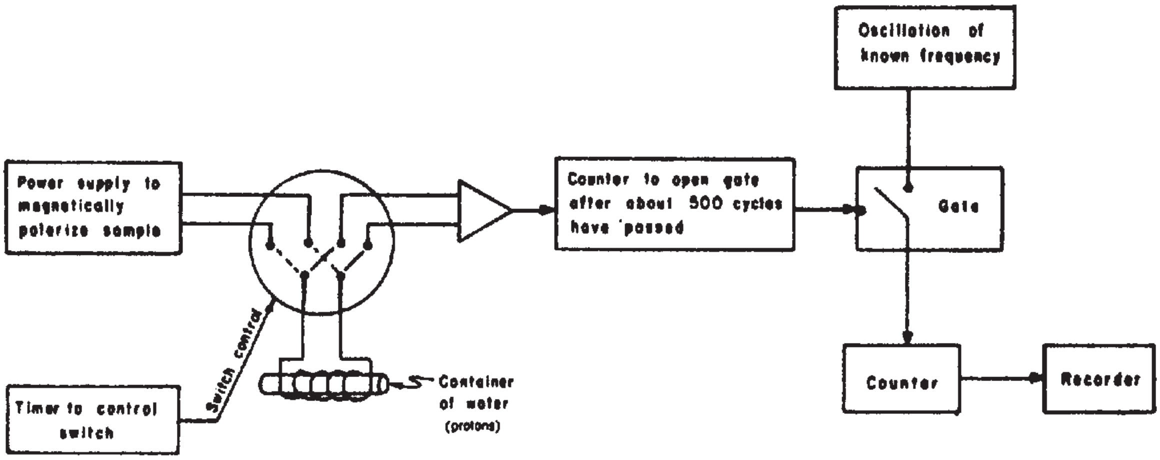

Figure 3.10. Proton-precession magnetometer. (From Sheriff, 1984.)

The essential components of this magnetometer include a source of protons, a polarizing magnetic field considerably stronger than that of the Earth and directed roughly normal to it (the direction of this field can be off by 45°), a pickup coil coupled tightly to the source, an amplifier to boost the minute voltage induced in the pickup coil, and a frequency-measuring device. The latter operates in the audio range because, from Equation (3.30b), $\nu = 2130$ Hz for $F_e = 50{,}000$ nT. It must also be capable of indicating frequency differences of about 0.4 Hz for an instrument sensitivity of 10 nT.

The proton source is usually a small bottle of water (the nuclear moment of oxygen is zero) or some organic fluid rich in hydrogen, such as alcohol. The polarizing field of 5 to 10 mT is obtained by passing direct current through a solenoid wound around the bottle, which is oriented roughly east–west for the measurement. When the solenoid current is abruptly cut off, the proton precession about the Earth's field is detected by a second coil as a transient voltage building up and decaying over an interval of ~ 3 s, modulated by the precession frequency. In some models the same coil is used for both polarization and detection. The modulation signal is amplified to a suitable level and the frequency measured. A schematic diagram is shown in Figure 3.10.

The measurement of frequency may be carried out by actually counting precession cycles in an exact time interval, or by comparing them with a very stable frequency generator. In one ground model, the precession signal is mixed with a signal from a local oscillator of high precision to produce low-frequency beats (≈ 100 Hz) that drive a vibrating reed frequency meter. Regardless of the method used, the frequency must be measured to an accuracy of 0.001% to realize the capabilities of the method. Although this is not particularly difficult in a fixed installation, it posses some problems in small portable equipment.

The proton-precession magnetometer's sensitivity (≈ 1 nT) is high, and it is essentially free from drift. The fact that it requires no orientation or leveling makes it attractive for marine and airborne operations. It has essentially no mechanical parts, although the electronic components are relatively complex. The main disadvantage is that only the total field can be measured. It also cannot record continuously because it requires a second or more between readings. In an aircraft traveling at 300 km/hr, the distance interval is about 100 m. Proton-precession magnetometers are now the dominant instrument for both ground and airborne applications.

3.4.4. Optically Pumped Magnetometer

A variety of scientific instruments and techniques has been developed using the energy in transferring atomic electrons from one energy level to another. For example, by irradiating a gas with light or radio-frequency waves of the proper frequency, electrons may be raised to a higher energy level. If they can be accumulated in such a state and then suddenly returned to a lower level, they release some of their energy in the process. This energy may be used for amplification (masers) or to get an intense light beam, such as that produced by a laser.

The optically pumped magnetometer is another application. The principle of operation may be understood from an examination of Figure 3.11a, which shows three possible energy levels, A_1, A_2, and B for a hypothetical atom. Under normal conditions of pressure and temperature, the atoms occupy ground state levels A_1 and A_2. The energy difference between A_1 and A_2 is very small [$\approx 10^{-8}$ electron volts (eV)], representing a fine structure due to atomic electron spins that normally are not all aligned in the

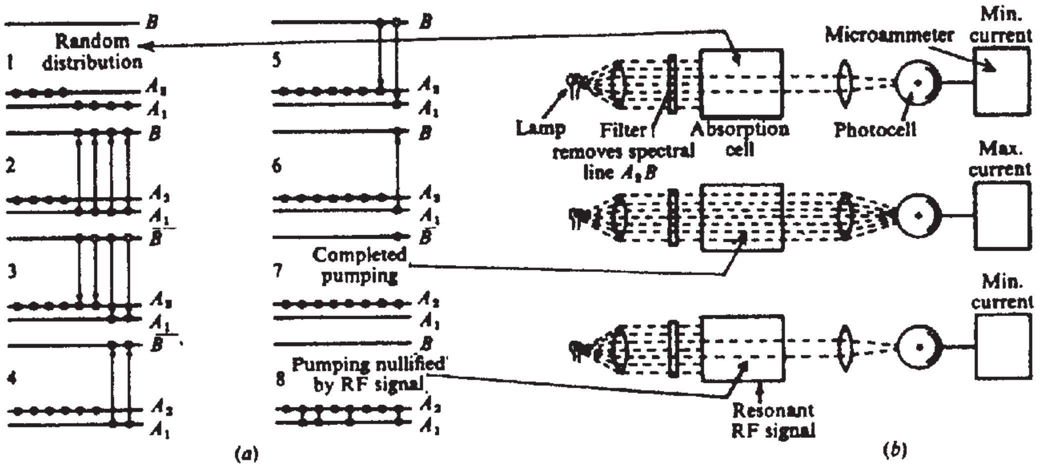

Figure 3.11. Optical pumping. (a) Energy level transitions. (b) Effect of pumping on light transmission.

same direction. Even thermal energies ($\approx 10^{-2}$ eV) are much larger than this, so that the atoms are as likely to be in level A_1 as in A_2.

Level B represents a much higher energy and the transitions from A_1 or A_2 to B correspond to infrared or visible spectral lines. If we irradiate a sample with a beam from which spectral line A_2B has been removed, atoms in level A_1 can absorb energy and rise to B, but atoms in A_2 will not be excited. When the excited atoms fall back to ground state, they may return to either level, but if they fall to A_1, they will be removed by photon excitation to B again. The result is an accumulation of atoms in level A_2.

The technique of overpopulating one energy level in this fashion is known as *optical pumping*. As the atoms are moved from level A_1 to A_2 by this selective process, less energy will be absorbed and the sample becomes increasingly transparent to the irradiating beam. When all atoms are in the A_2 state, a photosensitive detector will register a maximum current, as shown in Figure 3.11b. If now we apply an RF signal, having energy corresponding to the transition between A_1 and A_2, the pumping effect is nullified and the transparency drops to a minimum again. The proper frequency for this signal is given by $\nu = E/h$, where E is the energy difference between A_1 and A_2 and h is Planck's constant [6.62×10^{-34} joule-seconds].

To make this device into a magnetometer, it is necessary to select atoms that have magnetic energy sublevels that are suitably spaced to give a measure of the weak magnetic field of the Earth. Elements that have been used for this purpose include cesium, rubidium, sodium, and helium. The first three each have a single electron in the outer shell whose spin axis lies either parallel or antiparallel to an external magnetic field. These two orientations correspond to the energy levels A_1 and A_2 (actually the sublevels are more complicated than this, but the simplification illustrates the pumping action adequately), and there is a difference of one quantum of angular momentum between the parallel and antiparallel states. The irradiating beam is circularly polarized so that the photons in the light beam have a single spin axis. Atoms in sublevel A_1 then can be pumped to B, gaining one quantum by absorption, whereas those in A_2 already have the same momentum as B and cannot make the transition.

Figure 3.12 is a schematic diagram of the rubidium-vapor magnetometer. Light from the Rb lamp is circularly polarized to illuminate the Rb vapor cell, after which it is refocused on a photocell. The axis of this beam is inclined approximately 45° to the Earth's field, which causes the electrons to precess about the axis of the field at the Larmor frequency. At one point in the precession cycle the atoms will be most nearly parallel to the light-beam direction and one-half cycle later they will be more antiparallel. In the first position, more light is transmitted through the cell than in the second. Thus the precession frequency produces a variable light intensity that flickers at the Larmor frequency. If the photocell signal is amplified and fed back to a coil wound on the cell, the coil–amplifier system becomes an oscillator whose frequency ν is given by

$$F = 2\pi\nu/\gamma_e \qquad (3.31)$$

where γ_e is the *gyromagnetic ratio of the electron*.

For Rb, the value of $\gamma_e/2\pi$ is approximately 4.67 Hz/nT whereas the corresponding frequency for $F_e = 50{,}000$ nT is 233 kHz. Because γ_e for the electron is known to a precision of about 1 part in 10^7 and because of the relatively high frequencies involved, it

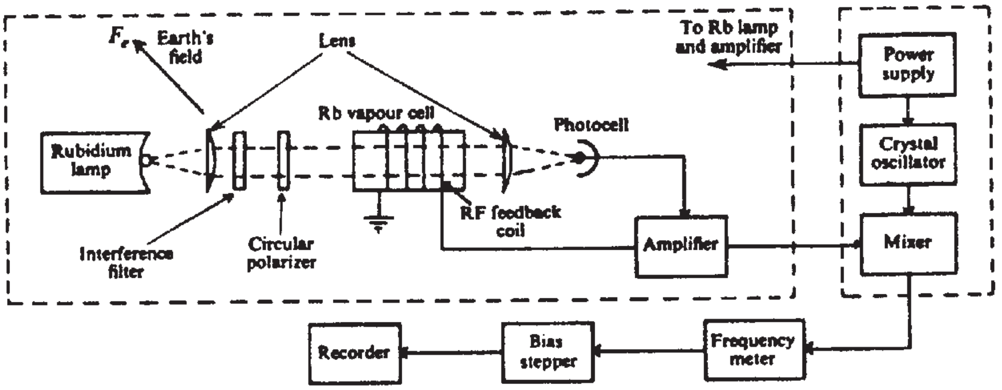

Figure 3.12. Rubidium-vapor magnetometer (schematic).

is not difficult to measure magnetic field variations as small as 0.01 nT with a magnetometer of this type.

3.4.5. Gradiometers

The sensitivity of the optically pumped magnetometer is considerably greater than normally required in prospecting. Since 1965, optically pumped rubidium- and cesium-vapor magnetometers have been increasingly employed in airborne gradiometers. Two detectors, vertically separated by about 35 m, measure dF/dz, the total-field vertical gradient. The sensitivity is reduced by pitch and yaw of the two birds. Major improvements by the Geological Survey of Canada involve reducing the vertical separation to 1 to 2 m and using a more rigid connection between the sensors. Gradient measurements are also made in ground surveys. The two sensors on a staff in the Scintrex MP-3 proton-magnetometer system, for example, measure the gradient to ±0.1 nT/m. Gradiometer surveys are discussed further in Section 3.5.5.

3.4.6. Instrument Recording

Originally the magnetometer output in airborne installations was displayed by pen recorder. To achieve both high sensitivity and wide range, the graph would be "paged back" (the reference value changed) frequently to prevent the pen from running off the paper. Today recording is done digitally, but generally an analog display is also made during a survey. Some portable instruments for ground work also digitally record magnetometer readings, station coordinates, diurnal corrections, geological and terrain data.

3.4.7. Calibration of Magnetometers

Magnetometers may be calibrated by placing them in a suitably oriented variable magnetic field of known value. The most dependable calibration method employs a *Helmholtz coil* large enough to surround the instrument. This is a pair of identical coils of N turns and radii a coaxially spaced a distance apart equal to the radius. The resulting magnetic field, for a current I flowing through the coils connected in series-aiding, is directed along the axis and is uniform within about 6% over a cylinder of diameter a and length $3a/4$, concentric with the coils. This field is given by

$$H \approx 9.0NI/a \qquad (3.32a)$$

where I is in microamperes, H in nanoteslas, and a in meters. Because H varies directly with the current, this can be written

$$\Delta H = 9.0N\Delta I/a \qquad (3.32b)$$

3.5. FIELD OPERATIONS

3.5.1. General

Magnetic exploration is carried out on land, at sea, and in the air. For areas of appreciable extent, surveys usually are done with the airborne magnetometer.

In oil exploration, airborne magnetics (along with surface gravity) is done as a preliminary to seismic work to establish approximate depth, topography, and character of the basement rocks. Since the susceptibilities of sedimentary rocks are relatively small, the main response is due to igneous rocks below (and sometimes within) the sediments.

Within the last few years it has become possible to extract from aeromagnetic data weak anomalies originating in sedimentary rocks, such as result from the faulting of sandstones. This results from (a) the improved sensitivity of magnetometers, (b) more precise determination of location with Doppler radar (§B.5), (c) corrections for diurnal and other temporal field variations, and (d) computer-analysis techniques to remove noise effects.

Airborne reconnaissance for minerals frequently combines magnetics with airborne EM. In most cases of followup, detailed ground magnetic surveys are carried out. The method is usually indirect, that is, the primary interest is in geological mapping rather than the mineral concentration per se. Frequently the association of characteristic magnetic anomalies with base-metal sulfides, gold, asbestos, and so on, has been used as a marker in mineral exploration. There is also, of course, an application for magnetics in the direct search for certain iron and titanium ores.

3.5.2. Airborne Magnetic Surveys

(a) General. In Canada and some other countries, government agencies have surveyed much of the country and aeromagnetic maps on a scale of 1 mile to the inch are available at a nominal sum. Large areas in all parts of the world have also been surveyed in the course of oil and mineral exploration.

The sensitivity of airborne magnetometers is generally greater than those used in ground exploration - about 0.01 nT compared with 10 to 20 nT. Because of the initial large cost of the aircraft and availability of space, it is practical to use more sophisticated equipment than could be handled in portable instruments; their greater sensitivity is useful in making measurements several hundred meters above the ground surface, whereas the same sensitivity is usually unnecessary (and may even be undesirable) in ground surveys.

(b) Instrument mounting. Aside from stabilization, there are certain problems in mounting the sensitive magnetic detector in an airplane, because the latter has a complicated magnetic field of its own. One obvious way to eliminate these effects is to tow the sensing element some distance behind the aircraft. This was the original mounting arrangement and is still used. The detector is housed in a streamlined cylindrical container, known as a *bird*, connected by a cable 30 to 150 m long. Thus the bird may be 75 m nearer the ground than the aircraft. A photograph of a bird mounting is shown in Figure 3.13a.

An alternative scheme is to mount the detector on a wing tip or slightly behind the tail. The stray magnetic effects of the plane are minimized by permanent magnets and soft iron or permalloy shielding strips, by currents in compensating coils, and by metallic sheets for electric shielding of the eddy currents. The shielding is a cut-and-try process, since the magnetic effects vary with the aircraft and mounting location. Figure 3.13b shows an installation with the magnetometer head in the tail.

(c) Stabilization. Since proton-precession and optically pumped magnetometers measure total field, the problem of stable orientation of the sensing element is minor. Although the polarizing field in the proton-precession instrument must not be parallel to the total-field direction, practically any other orientation will do because the signal amplitude becomes inadequate only within a cone of about 5°.

Stabilization of the fluxgate magnetometer is more difficult, because the sensing element must be maintained accurately in the F axis. This is accomplished with two additional fluxgate detectors that are oriented orthogonally with the first; that is, the three elements form a three-dimensional orthogonal coordinate system. The set is mounted on a small platform that rotates freely in all directions. When the sensing fluxgate is accurately aligned along the total-field axis, there is zero signal in the other two. Any tilt away from this axis produces a signal in the control elements that drive servomotors to restore the system to the proper orientation.

(d) Flight pattern. Aeromagnetic surveys almost always consist of parallel lines (Fig. 3.13c) spaced anywhere from 100 m to several kilometers apart. The heading generally is normal to the main geologic trend in the area and altitude usually is maintained at fixed elevations, the height being continuously recorded by radio or barometric altimeters. It is customary to record changes in the Earth's field with time (due to diurnal or more sudden variations) with a recording magnetometer on the ground. A further check generally is obtained by flying several cross lines, which verify readings at line intersections.

A *drape survey*, which approximates constant clearance over rough topography, is generally flown with a helicopter. It is often assumed that drape surveys minimize magnetic terrain effects, but Grauch and Campbell (1984) dispute this. Using a uniformly magnetized model of a mountain–valley system, four profiles (one level, the others at different ground clearance) all showed terrain effects. However, Grauch and Campbell recommend drape surveys over level-flight surveys because of greater sensitivity to small targets, particularly in valleys. The disadvantages of draped surveys are higher cost, operational problems, and less sophisticated interpretation techniques.

(e) Effect of variations in flight path. Altitude differences between flight lines may cause herringbone patterns in the magnetic data. Bhattacharyya (1970) studied errors arising from flight deviations

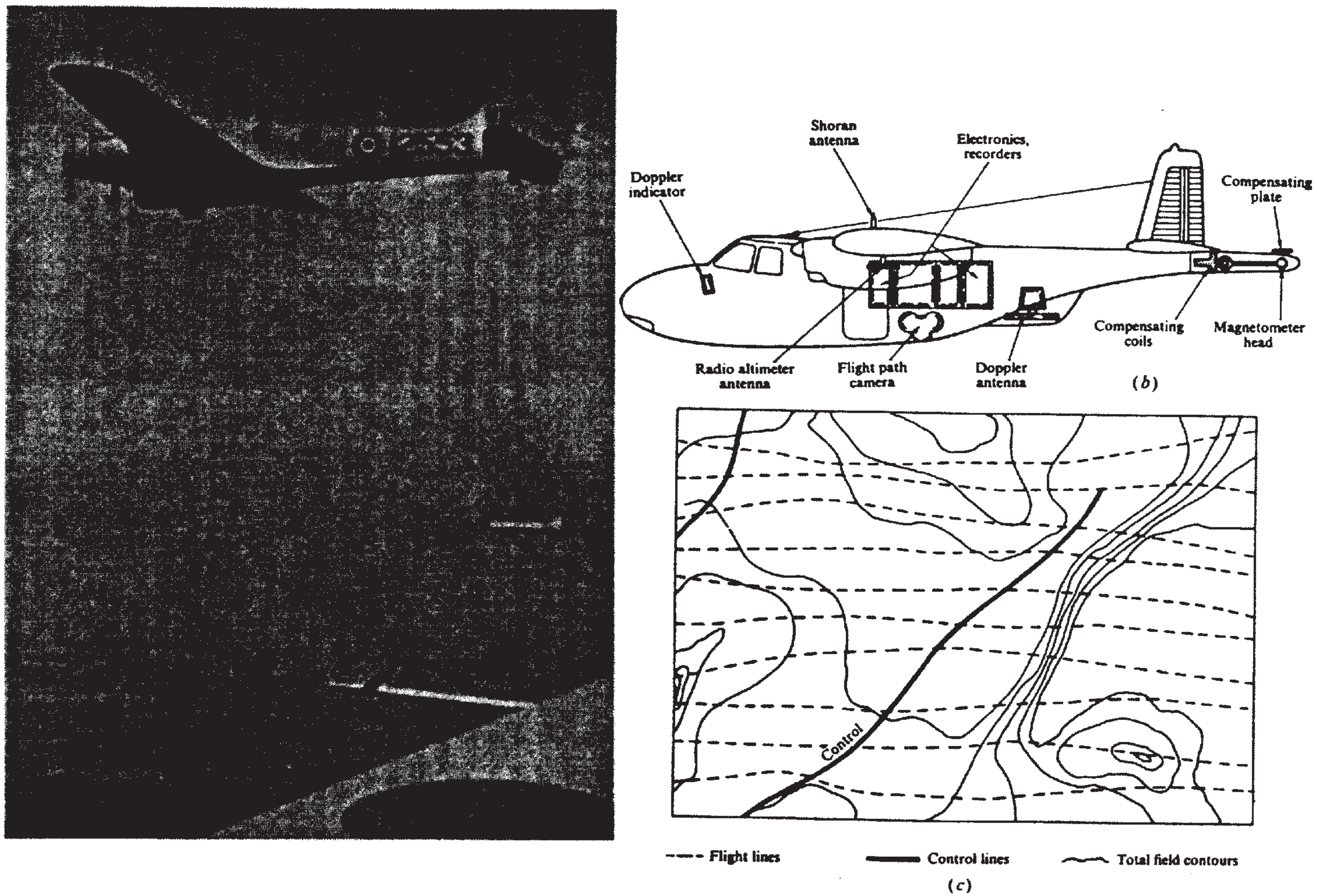

Figure 3.13. Airborne magnetics. (a) Magnetometer in a bird. (b) Magnetometer in a tail mounting. (c) Flight pattern and magnetic map.

over an idealized dike (prism) target. Altitude and heading changes produced field measurement changes that would alter interpretations based on anomaly shape measurements, such as those of slope. Such deviations are especially significant with high-resolution data.

(f) Aircraft location. The simplest method of locating the aircraft at all times, with respect to ground location, is for the pilot to control the flight path by using aerial photographs, while a camera takes photos on strip film to determine locations later. The photos and magnetic data are simultaneously tagged at intervals. Over featureless terrain, radio navigation (see §B.6) gives aircraft position with respect to two or more ground stations, or Doppler radar (§B.5) determines the precise flight path. Doppler radar increasingly is employed where high accuracy is required.

(g) Corrections to magnetic data. Magnetic data are corrected for drift, elevation, and line location differences at line intersections in a least-squares manner to force ties. Instrument drift is generally not a major problem, especially with proton and optically pumped magnetometers whose measurements are absolute values.

The value of the main magnetic field of the Earth is often subtracted from measurement values. The Earth's field is usually taken to be that of the *International Geomagnetic Reference Field* (IGRF) model.

A stationary base magnetometer is often used to determine slowly varying diurnal effects. Horizontal gradiometer arrangements help in eliminating rapid temporal variations; the gradient measurements do not involve diurnal effects. Usually no attempt is made to correct for the large effects of magnetic storms.

(h) Advantages and disadvantages of airborne magnetics. Airborne surveying is extremely attractive for reconnaissance because of low cost per kilometer (see Table 1.2) and high speed. The speed not only reduces the cost, but also decreases the effects of time variations of the magnetic field. Erratic near-surface features, frequently a nuisance in ground work, are considerably reduced. The flight elevation may be chosen to favor structures of certain size and depth. Operational problems associated with irregular terrain, sometimes a source of difficulty in ground magnetics, are minimized. The data are smoother, which may make interpretation easier. Finally, aeromagnetics can be used over water and in regions inaccessible for ground work.

The disadvantages in airborne magnetics apply mainly to mineral exploration. The cost for surveying small areas may be prohibitive. The attenuation of near-surface features, apt to be the survey objective, become limitations in mineral search.

3.5.3. Shipborne Magnetic Surveys

Both the fluxgate and proton-precession magnetometers have been used in marine operations. There are no major problems in ship installation. The sensing element is towed some distance (150 to 300 m) astern (to reduce magnetic effects of the vessel) in a watertight housing called a *fish*, which usually rides about 15 m below the surface. Stabilization is similar to that employed in the airborne bird. Use of a ship rather than an aircraft provides no advantage and incurs considerable cost increase unless the survey is carried out in conjunction with other surveys, such as gravity or seismic. The main application has been in large-scale oceanographic surveying related to earth physics and petroleum search. Much of the evidence supporting plate tectonics has come from marine magnetics.

3.5.4. Ground Magnetic Surveys

(a) General. Magnetic surveying on the ground now almost exclusively uses the portable proton-precession magnetometer. The main application is in detailed surveys for minerals, but ground magnetics are also employed in the followup of geochemical reconnaissance in base-metal search. Station spacing is usually 15 to 60 m; occasionally it is as small as 1 m. Most ground surveys now measure the total field, but vertical-component fluxgate instruments are also used. Sometimes gradiometer measurements (§3.5.5) are made.

(b) Corrections. In precise work, either repeat readings should be made every few hours at a previously occupied station or a base-station recording magnetometer should be employed. This provides corrections for diurnal and erratic variations of the magnetic field. However, such precautions are unnecessary in most mineral prospecting because anomalies are large (> 500 nT).

Since most ground magnetometers have a sensitivity of about 1 nT, stations should not be located near any sizeable objects containing iron, such as railroad tracks, wire fences, drill-hole casings, or culverts. The instrument operator should also not wear iron articles, such as belt buckles, compasses, knives, iron rings, and even steel spectacle frames.

Apart from diurnal effects, the reductions required for magnetic data are insignificant. The vertical gradient varies from approximately 0.03 nT/m at the poles to 0.01 nT/m at the magnetic equator. The latitude variation is rarely > 6 nT/km. Thus elevation and latitude corrections are generally unnecessary.

The influence of topography on ground magnetics, on the other hand, can be very important. This is apparent when taking measurements in stream gorges, for example, where the rock walls above the station frequently produce abnormal magnetic lows. Terrain anomalies as large as 700 nT occur at steep (45°) slopes of only 10 m extent in formations containing 2% magnetite ($k = 0.025$ SI unit) (Gupta and Fitzpatrick, 1971). In such cases, a terrain correction is required, but it cannot be applied merely as a function of topography alone because there are situations (for example, sedimentary formations of very low susceptibility) in which no terrain distortion is observed.

A terrain smoothing correction may be carried out by reducing measurements from an irregular surface $z = h(x, y)$ to a horizontal plane, say $z = 0$, above it. This can be done approximately by using a Taylor series (§A.5) with two terms:

$$Z(x, y, 0) = Z(x, y, h) - h(\partial Z/\partial z)_{z=h} \quad (3.33)$$

3.5.5. Gradiometer Surveys

The gradient of **F** is usually calculated from the magnetic contour map with the aid of templates. There is, however, considerable merit in measuring the vertical gradient directly in the field. It is merely necessary to record two readings, one above the other. With instrument sensitivity of 1 nT, an elevation difference of ≈ 1 m suffices. Then the vertical gradient is given by

$$\partial F/\partial z = (F_2 - F_1)/\Delta z$$

where F_1 and F_2 are readings at the higher and lower elevations, and Δz is the separation distance.

Discrimination between neighboring anomalies is enhanced in the gradient measurements. For example, the anomalies for two isolated poles at depth h separated by a horizontal distance h yield separate peaks on a $\partial F/\partial z$ profile but they have to be separated by 1.4 h to yield separate anomalies on an F profile. The effect of diurnal variations is also minimized, which is especially beneficial in high magnetic latitudes. For most of the simple shapes discussed in Section 3.6 (especially for the isolated pole, finite-length dipole, and vertical contact of great depth extent), better depth estimates can be made from the first vertical-derivative profiles than from either the Z or F profiles. For features of the first two types, the width of the profile at $(\partial Z/\partial z)_{\max}/2$ equals the depth within a few percent. For the vertical contact, half the separation between maximum and minimum values equals the depth. Gradiometer measurements are valuable in field continuation calculations (§3.7.5).

Ground gradiometer measurements (Hood and McClure, 1965) have recently been carried out for gold deposits in eastern Canada in an area where the overburden is only a few meters thick. The host quartz was located because of its slightly negative susceptibility using a vertical separation of 2 m and a station spacing of ≈ 1 m. Gradiometer surveys have also been used in the search for archeological sites and artifacts, mapping buried stone structures, forges, kilns, and so forth (Clark, 1986; Wynn, 1986).

Vertical gradient aeromagnetic surveys (Hood, 1965) are often carried out at 150 to 300 m altitude. Detailed coverage with 100 to 200 m line spacing is occasionally obtained at 30 m ground clearance.

Two magnetometers horizontally displaced from each other are also used, especially with marine measurements where they may be separated by 100 to 200 m. This arrangement permits the elimination of rapid temporal variations so that small spatial anomalies can be interpreted with higher confidence.

3.6. MAGNETIC EFFECTS OF SIMPLE SHAPES

3.6.1. General

Because ground surveys (until about 1968) measured the vertical-field component, whereas airborne surveys measured the total field, both vertical-component and total-field responses will be developed. Depth determinations are most important and lateral extent less so, whereas dip estimates are the least important and quite difficult. In this regard, aeromagnetic and electromagnetic interpretation are similar. In petroleum exploration the depth to basement is the prime concern, whereas in mineral exploration more detail is desirable. The potentialities of high resolution and vertical-gradient aeromagnetics are only now being exploited to a limited extent.

As in gravity and electromagnetics, anomalies are often matched with models. The magnetic problem is more difficult because of the dipole character of the magnetic field and the possibility of remanence. Very simple geometrical models are usually employed: isolated pole, dipole, lines of poles and dipoles, thin plate, dike (prism), and vertical contact. Because the shape of magnetic anomalies relates to the magnetic field, directions in the following sections are with respect to magnetic north (the x direction), magnetic east, and so forth, the z axis is positive downward, and we assume that locations are in the northern hemisphere. We use I for the field inclination, ξ for