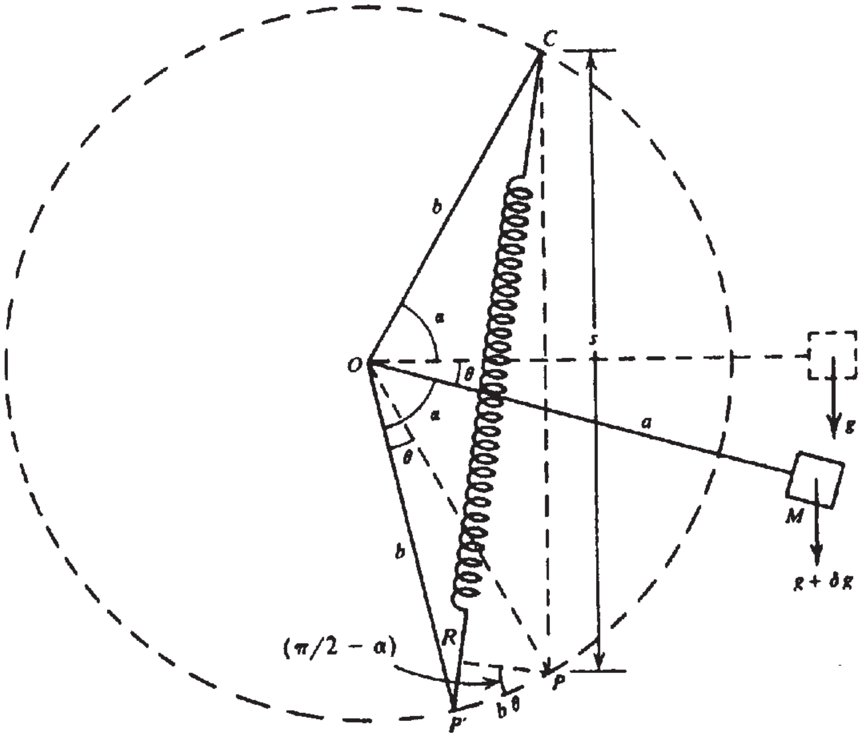

Figure 2.14. Basic principle of the Worden gravimeter.

circle to P' and

$$M(g + \delta g)\,a\cos\theta = kb(s + \delta s)\cos(\alpha + \theta/2)$$

When $\theta \approx 0$, to the first approximation this becomes

$$\begin{aligned} M(g + \delta g)\,a &= kb(s + \delta s)\{\cos\alpha - (\theta/2)\sin\alpha\} \\ &= kb(s + \delta s)\{\cos\alpha - (\delta s/2b)\tan\alpha\} \\ &= kb\{s\cos\alpha - \delta s(s/2b)\tan\alpha + \delta s\cos\alpha\} \end{aligned}$$

Subtracting the first moment equation to eliminate g, we get

$$Ma\,\delta g = kb\{\cos\alpha - (s/2b)\tan\alpha\}\,\delta s$$

Using the relation $\sin\alpha = s/2b$, we finally get

$$\delta g = (k/M)(b/a)(\cos 2\alpha/\cos\alpha)\,\delta s \quad (2.37)$$

As in the LaCoste–Romberg meter, the sensitivity can be increased by decreasing the factors (k/M) and (b/a); in addition the factor $(\cos 2\alpha/\cos\alpha)$ approaches zero when α approaches 45°, thus furnishing another method of obtaining high sensitivity. In practice the sensitivity is about 0.01 mGal.

Like the LaCoste–Romberg instrument, the Worden meter is read by measuring the force required to restore the beam to the horizontal position.

(g) Calibation of gravimeters. Both the Worden and LaCoste–Romberg meters are null instruments and changes in gravity are shown as arbitrary scale divisions on a micrometer dial. There are several methods for converting these scale readings to gravity units.

Theoretically calibration can be carried out by tilting because a precise geometrical system is involved, but this is not the usual procedure. Generally, readings are taken at two or more stations where values of g are already known. If the value of δg between the stations is large enough to cover a reasonable fraction of the instrument range, a linear response is usually assumed between them. However, one should occupy several additional stations if possible.

2.5. FIELD OPERATIONS

2.5.1. Land Surveys

Gravity exploration is carried out both on land and at sea. Although some attempts have been made to develop an airborne instrument, this mode of operation is not yet practical (Paterson and Reeves, 1985).

The distinction between reconnaissance and detailed field work is based on the objective, that is, whether the purpose is to find features of interest or to map them. Station spacings in field work with the gravimeter vary from 20 km to as little as 5 m. The station interval is usually selected on the basis of assumed depth and size of the anomalies sought. For oil exploration, one station per 2 to 4 km^2 is desirable because structures associated with oil accumulation are usually larger than this and hence their anomalies would not be missed with such spacing. While a more-or-less uniform grid of stations is desirable, stations are often run on loops that are operationally easier. Stations 0.5 to 1.0 km apart on loops roughly 6 × 6 km in size might be typical for a petroleum survey.

In mineral exploration, gravity is normally employed as a secondary detail method for confirmation and further analysis of anomalies already outlined by magnetic and/or electrical techniques. The spacing is determined mainly by knowledge gained from the earlier surveys. Measurements are usually made at the same locations as the magnetic or electrical stations, commonly 15 to 30 m apart.

Microgravity engineering and archaeological surveys (for example, searching for cavities or bedrock) sometimes involve station spacing as close as 1 m (Arzi, 1975).

Field measurements with modern gravimeters are straightforward. The gravimeter must be leveled precisely for each reading. It may be difficult to get a stable null in swampy ground and when the wind is strong, but extra care and time generally give an acceptable measurement. Similar problems arise in marine gravity work using instruments that rest on the sea floor. For reasonable speed of operation, a vehicle normally is used for getting from station to station.

Precision is required in surveying gravity stations. Achieving the required precision (10 cm in elevation and about 30 m in latitude for 0.03 mGal accuracy) often involves the major cost of field work. Gravity measurements typically proceed much faster than the surveying, and three or four survey teams may be required to keep ahead of one meter operator.

Inertial navigation sometimes cuts the cost of determining location and elevation, especially where helicopter transport is used in areas of difficult access (LaFehr, 1980). An inertial navigation system (§B.7) senses acceleration by means of three orthogonal accelerometers mounted on a gyroscopically stabilized platform; changes in horizontal and vertical position are determined by integrating twice over time. Very small errors tend to accumulate rapidly to produce large errors, but these can be reduced to acceptable amounts if the helicopter stops every 3 to 5 min during which time the drift rate can be determined. This time interval is compatible with the travel time from station to station. Lynch and King (1983) claim 0.8 m elevation accuracy and 15 m horizontal accuracy in a survey in the mountainous overthrust belt of the Rocky Mountains, to yield Bouguer values with 0.3 mGal accuracy. In a high-precision survey of a limited area in northern Canada checked by leveling, elevations were determined to 0.9 m and horizontal positioning to 0.43 m, so inertial navigation can achieve remarkable accuracy. With a helicopter survey, stations can be located on a more uniform grid than with land surveys (which are usually run around the perimeter on traverses), so that interpolation errors are considerably reduced.

2.5.2. Drift Correction

Gravimeters change their null reading value gradually with time. This *drift* results mainly from creep in the springs and is usually unidirectional. Modern instruments, however, have very little drift. Gravity readings also change with time becuase of tidal effects (§2.3.2f).

The net result of drift and tidal effects is that repeated readings at one station give different values. *Drift correction* is accomplished by reoccupying some stations. The maximum time between repeat readings depends on the accuracy desired, but is usually 3 or 4 hr. A drift curve is shown in Figure 2.15. Its oscillatory shape is determined by tidal effects. It is not necessary to use the same station for checking drift because any station can be reoccupied. Intermediate gravity stations occupied only once can then be corrected for the drift that occurred.

If the meter movement is not clamped between readings or is subjected to sudden motion or jarring (as during transport), somewhat erratic changes (called *tears* or *tares*) may be produced. If the instrument is bumped, it is wise to reread a known station immediately. Since there is no way of allowing for erratic changes, we can only correct those points occupied while the drift curve is smooth.

2.5.3. Marine Surveys

(a) Locating marine stations. Considerable gravity work has been done on the surface of water-covered areas and also on the sea floor. Locating the station is usually done by using a radionavigation system such as Shoran, Raydist, or RPS (see §B.6). The accuracy of offshore location is usually lower than on land but elevation determination is not a problem if appropriate allowance is made for tidal variations.

(b) Remote control systems. Standard gravimeters have been adapted for operation on the sea floor to depths of 200 m. This method of measurement is suitable for most inland waters and coastal areas. The meter is enclosed in a pressure housing that is supported on a squat tripod with disk feet. About

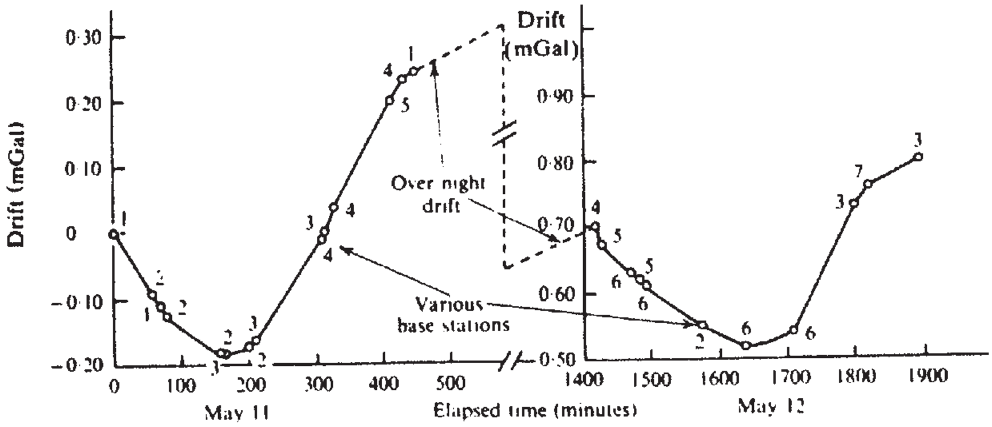

Figure 2.15. Gravimeter drift during a field survey.

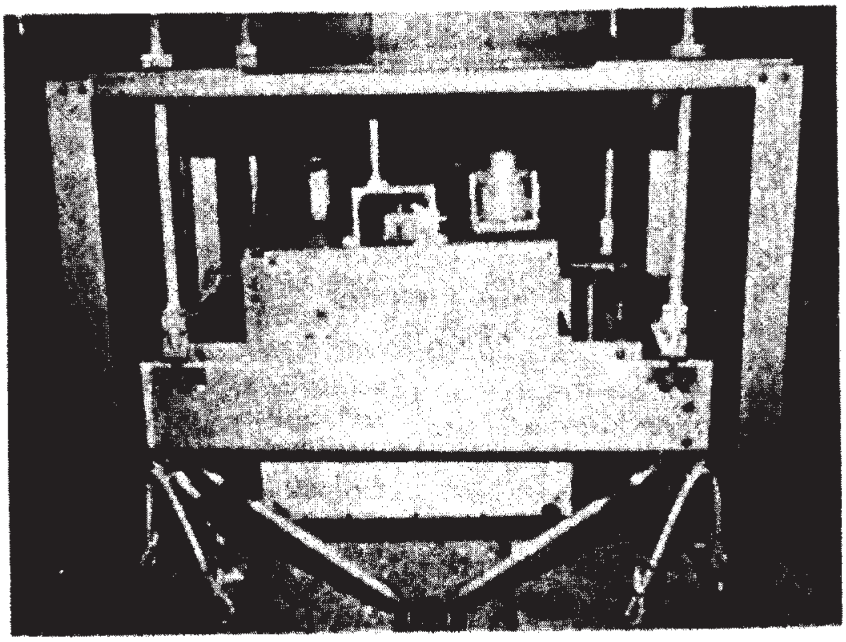

Figure 2.16. Photograph of a shipboard gravimeter.

half the total weight of the assembly is in the tripod in order to provide maximum stability when it is resting on the bottom; the overall weight of one model is 300 kg. The assembly is connected to a ship by a cable from which it is lowered into position on the bottom. Leveling is achieved by small motors that raise or lower the disk feet.

Although the high sensitivity of this equipment is an advantage, operation in deep water is slow because the assembly must be raised to the surface between stations. A problem in reoccupying stations is that the sea floor location may be different from that previously occupied, even when the surface location is identical. This method is now little used.

(c) Shipboard operations and the Eötvös correction. Shipboard gravimeters (Fig. 2.16) are used for most gravity measurements at sea. Shipboard gravimeters are mounted on an elaborate gyro-stabilized platform (Valliant and LaCoste, 1976) located in the part of a ship where there is minimum movement due to roll and pitch.

If a gravimeter has a velocity during a measurement, the centrifugal force acting on the meter is different from that when it is at rest. An eastward component of velocity adds to the velocity owing to the rotation of the Earth and hence increases the centrifugal force and decreases the gravity reading. A westward component of velocity has the opposite effect. A northward component creates a new component of centrifugal force, which is added vectorially to the first. The correction for the velocity of the meter, Δg_V, called the *Eötvös correction*, is given by

$$\Delta g_V = 4.040V \cos\phi \sin\alpha + 0.001211V^2 \text{ mGal} \quad (2.38a)$$

$$\Delta g_V = 7.503V' \cos\phi \sin\alpha + 0.004154V'^2 \text{ mGal} \quad (2.38b)$$

where V is in kilometers per hour, V' in knots, ϕ is the latitude, and α is the course direction with respect to true north. The accuracy of shipboard gravity depends mainly on the accuracy of the Eötvös correction.

The error in the Eötvös correction due to errors in V and α is

$$d(\Delta g_V) = (0.0705V \cos\phi \cos\alpha)\, d\alpha + (4.040 \cos\phi \sin\alpha + 0.002422V)\, dV \quad (2.39)$$

with V and dV in kilometers per hour and $d\alpha$ in degrees. Thus the sensitivity to velocity error is greatest for an east–west course and the sensitivity to course-direction error is greatest for a north–south course. Assuming that the velocity at the moment of gravity reading involves an uncertainty of 0.2 km/hr and instantaneous heading error of 1°, $\phi = 40°$, and $V = 10$ km/hr, then $d(\Delta g_V) = 0.62$ mGal for an east–west course and 0.54 mGal for a north–south course.

2.5.4. Airborne Gravity

The main difficulty with airborne gravity surveys arises from very large and rapid changes in g_{obs} caused by changes in the aircraft altitude, linear acceleration, roll, and heading. These effects can be corrected for in shipborne gravity work because changes are slow and the velocity is low.

Hammer (1983) tells of using a helicopter flying (in the middle of the night to avoid air turbulence) at a speed of 50 to 100 km/hr at elevations of 300 to 4,000 m using an autopilot directed by a navigation-system computer (a human pilot is not sufficiently precise). His data, smoothed over a 2 min window (2 to 4 km), suggest that airborne gravity would be useful for regional studies and reconnaissance of large anomalies. Brozena (1984) achieved an accuracy of 5 mGal averaged over 20 km.

2.6. GRAVITY DATA PROCESSING

2.6.1. Noise, Regionals, and Residuals

Because a Bouguer map shows horizontal differences in the acceleration of gravity, only horizontal changes in density produce anomalies. Purely vertical changes in density produce the same effect everywhere and so no anomalies result.

The gravity field is a superposition of anomalies resulting from density changes (anomalous masses) at various depths. Some anomalous masses lie at depths in the zone of interest, some result from deeper masses, and some from shallower ones. As the source of an anomaly deepens, the anomlay become more spread out and its amplitude decreases. The smoothness (or apparent wavelength) of anomalies is generally roughly proportional to the depth of the lateral density changes.

The depth range we wish to emphasize depends on the objectives of the interpretation. Shallow anomalies are of interest in mineral exploration but are usually regarded as undesirable noise in petroleum exploration. As in any geophysical technique, the most useful factor in interpretation is knowledge of the local geology.

Whereas it is possible for a distributed anomalous mass to give an anomaly that appears to originate from a more concentrated deeper mass, a concentrated mass cannot appear to originate deeper. The horizontal extent and smoothness of an anomaly is therefore usually a measure of the depth of the anomalous mass, and this property can be used to partially separate the effects of anomalous masses that lie within a depth zone of interest from the effects of both shallower and deeper masses.

The effects of shallow masses (*near-surface noise*) are usually of short wavelength. They can be removed largely by filtering out (smoothing) short-wavelength anomalies. The effects of deep masses are called the *regional*. The gravity field after near-surface noise and the regional have been removed is called the *residual*; it presumably represents effects of the intermediate zone of interest.

The major problem in gravity interpretation is separating anomalies of interest from the overlapping effects of other features; usually the main obscuring effects result from deeper features. *Residualizing* attempts to remove the regional so as to emphasize the residual. However, the separation usually is not complete; both regional and residual are distorted by the effects of each other.

Residualizing can also be thought of as predicting the values expected from deep features and then subtracting them from observed values, so as to leave the shallower effects. The expected value of the regional is generally determined by averaging values in the area surrounding the station. Several methods of removing the unwanted regional are described in the next section. Gupta and Ramani (1982) discuss the application of different residualizing methods.

Gravity station locations should be shown on the final map to aid in distinguishing residuals that are well controlled from those possibly resulting from interpolation.

The result obtained by smoothing profiles or contours is inevitably biased by the interpreter, but this is not necessarily bad. If the interpreter is experienced and uses additional geologic knowledge to guide him, it may be a decided advantage. It should be noted that nonsmoothing methods of residualizing also involve subjective elements, such as the choice of order for surface fitting, of grid dimensions in grid residualizing, and so on.

2.6.2. Graphical Residualizing

Graphical residualizing is done by smoothing either profiles or maps. A simple example of removing the regional by smoothing is illustrated in Figure 2.17. The profile in Figure 2.17a shows disturbances of different sizes; the smooth, nearly linear slope is the regional. In Figure 2.17b, the regional contours are regular and the residual obtained by subtracting the smoothed contours from the map values should be reliable.

The emphasis in drawing a smooth regional should be on "smooth" and most of the errors or failures in residualizing are caused by the regional not being sufficiently smooth. "Smooth" implies both smooth in shape and systematic in contour interval. Often profiles are plotted for several parallel lines, generally in the dip direction. Smooth regionals are then drawn on these parallel lines, making certain that they are consistent on all profiles. Often cross profiles are drawn linking the parallel lines into a grid to ensure that the regional is consistent over the grid. This approach is especially suitable when the regional trend is mainly unidirectional. If the survey has been carried out with close, uniform spacing of stations and lines, the station values themselves can be used instead of contour values to plot the profiles, thereby reducing errors because of contour interpolation.

Once the regional has been contoured, the residuals are obtained by subtracting the regional from the Bouguer map, either graphically or numerically. Graphical residualizing is sometimes done by drawing contours of constant difference through the points where regional and observed contours intersect.

When the regional is so irregular that the directional trend is not immediately apparent or when there are several superimposed regional systems, residualizing may be done iteratively, that is, one first determines and removes the most obvious regional and then finds a second-order regional from the first-order residual, and so on.

2.6.3. Surface-Fitting Residualizing Methods

The regional is sometimes represented by a low-order analytic surface. The parameters of the analytic surface are usually determined by a least-squares fit (Agocs, 1951) or some similar operation. How closely the surface fits the data depends on the order of the surface and the magnitude of the area being fitted. Nettleton (1976) illustrates orders of fit for a one-dimensional case (Fig. 2.18). The regional surface is often that given by a polynomial or the low-order components of a 2D-Fourier surface [Eq. (A.52a)]. The selection of order is usually made by examination of trial fits of several different orders.

Surface fitting is sometimes done to isolate and emphasize trends. Results from Coons, Woolard, and Hershey (1967) are shown in Figure 2.19. The trend becomes more evident as the order increases up to some point, about tenth order for the data of Figure 2.19. The residual for low order still contains appreciable regional trend and thus low orders are not very effective in separating the regional from the residual. Likewise, high-order surfaces are not effective because much of the sought-after anomaly is mixed with the regional in the surface fit.

2.6.4. Empirical Gridding Methods

Gridding provides a simple way of predicting the regional by regarding it as the average value of gravity in the vicinity of the station (Griffin, 1949). Usually the values averaged are those on the circumference of a circle centered at the station:

$$\overline{g(r)} = (1/2\pi)\int_0^{2\pi} g(r,\theta)\, d\theta \qquad (2.40)$$