Chapter 6

Lagrangian-Style Subsurface Current Measurements Through Tracking of Subsurface Drifters

Chapter Outline

Because the oceans constitute a large and complex structure, surface currents provide only a portion of the database required to advance the science of oceanic water circulation dynamics. It is, therefore, important to measure currents beneath the surface Ekman layer, which are themselves complex. Subsurface current measurements are needed for the study of the general characteristics of oceanic water motion and to determine transport of energy, materials, and organisms such as plankton. Dense arrays of continuously tracked floats are desirable to describe the structure of synoptic circulation features.

But to efficiently establish mean flow, long-term observations from a float array of low but statistically uniform density are even more important. The extensive and remarkable developments in the field of underwater sound made during World War II placed in oceanographers' hands several efficient means of making subsurface current measurements by a variety of underwater acoustic methods. These have become powerful tools for measuring ocean circulation, mainly because of acoustic signals' ability to travel long distances in water and the inherently noninvasive nature of measurement. The following sections of this chapter describe various methods employed for measurements of oceanic subsurface currents and gyre systems.

6.1. SURFACE-TRACKABLE SUBSURFACE DRIFTERS

As noted in Chapter 2, the oldest method of Lagrangian-style subsurface current observation was the use of drogues. These drogues, maintained at the desired depth of measurements, were of various designs, such as wooden or metal crosses (popularly known as *biplanar crossed vanes*), sail drogues, or parachutes that offer the largest possible drag at the level of water current measurement. All these devices had to be adequately weighted to reduce the wire angle of the suspension wire and to keep the drogue at the desired depth. The drogues were connected by fine wires to small surface floats or buoys, equipped with identification signs such as numbered signaling flags for daytime visual observation, flashing lights for nighttime visual observation, or radar reflectors for remote detection through electromagnetic techniques. The data derived from each drogue consisted of a series of successive positions of the surface (visible) part of the drogue, determined at known times. The positions were determined by Long Range Navigation (LORAN) or radar. These types of subsurface Lagrangian drifters have historically seen the widest application in oceanographic studies, primarily because of their simplicity of

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construction and their cost effectiveness. Usually many drogues launched at different depths are tracked at nearly the same time. Drogue measurements have revealed some interesting results (Merritt et al., 1969).

The most commonly used subsurface drifters are parachutes. They are designed to fully open at a prescribed depth. The drogue depth is determined by the length of the wire connected to the supporting surface raft/buoy and the ballast weight attached to the parachute. Performance evaluation studies conducted under steady water-flow conditions have revealed that velocity-dependent shapes such as those of parachute drogues are unsuitable for measurement of small flows (Vachon, 1977). Most parachutes are made of nylon, which is approximately 12 percent denser than seawater. As a result, a nylon chute tends to hang down in closed conditions. In practice, these drogues have to be held open by devices such as rings or spreaders and must be made as neutrally buoyant as possible. Results of tow-tank tests have indicated that a weighted sail drogue, when tethered in line with the center of pressure, will align itself perpendicularly to the prevailing flow due to its hydrodynamic characteristics. Some drifters are fitted with canvas "window-blind" drogues to study currents at a depth given by the length of the drogue line. Graphical illustration of such a drogue is given in *Guide to ARGOS Systems,* Chapter 3, page 4. The telephonically tracked floats described in Chapter 3 can also be configured to measure subsurface currents. In this configuration, the two modules are deployed separately, connected with a rope line, and the four donut-shaped floats are attached on the surface module. The design is quite compact, modular, and flexible. The relatively small height of the drogue allows studies in highly stratified environments, with good vertical resolution of the velocity field, unlike the World Ocean Circulation Experiment (WOCE) open-ocean drifter design.

There are several problems associated with subsurface drogues. For realistic measurement of subsurface currents using the drogue method, it is important that the drogue move with the same velocity as the surrounding water. This requires that the drag exerted at the drogue be substantially greater than that exerted at the surface float, suspension cable, and other parts of the system. In practice, however, the surface float, the position of which is considered as that of the subsurface drogue, is constantly subject to the drag forces of surface-shear current, tension on the connecting tether, and the dynamics of waves and swells. In addition, the elasticity of the suspension cable with variable drags at the drogue will cause some up-and-down motion of the drogue, which traces the flow supposedly at a constant depth. In a dynamic environment, all these forces combine to introduce large errors in measurements, even in a system where drag characteristics of the drogue under steady-flow conditions are known. Furthermore, the surface-float-induced dynamic loading on a drogue in severe environments can shorten the life of the whole system.

In the midst of numerous environment-related problems, the data collected from subsurface drogue measurements tend to suffer from inaccuracies of various kinds. In the absence of alternate convenient techniques, the drogues were widely used in the past, and the data derived from such measurements provided valuable information on the rather complex water circulation features at depths a few hundred meters below the ocean surface (Merritt et al., 1969).

Interestingly, the validity of HF Doppler radar techniques for remote measurement of currents in the upper layers of the ocean surface (describe in Chapter 4) was first tested and convincingly proved by a series of intercomparison measurements using subsurface drogues deployed in the upper layers of the ocean (Stewart and Joy, 1974). In this experiment, the current was measured by tracking the positions of parachute drogues placed near the surface of the ocean at varying depths in the range of 2–4 meters below the surface. The drogues had a surface float that was tracked with accurate microwave radar. Their positions were measured approximately every 10–20 min, with a relative accuracy of ± 2 m. The mean direction of the current was obtained from a straight line drawn through the positions, and the mean speed was determined from the distance the drogue moved in 1 hour. The close agreement, within a few cm/s, between the drogue measurements and the nonintrusive measurements made by the HF Doppler radar, in fact, started the "radio scatter measurements revolution" that is witnessed today.

6.2. SATELLITE-RECOVERED POP-UP DRIFTERS

It has been observed that the surface-trackable subsurface drogue system described in the preceding section do not permit the desired true measurement of subsurface currents, unaffected by extraneous influences, because the current–tracing subsurface drogue is "tied" to a float that is sliding on a wind–affected and wave–laden ocean surface. Because a "chained" drogue cannot freely move with the surrounding water mass, the trajectories traced by the drogue are only approximations to the true trajectories of the water parcels at the depths of the drogue. The ideal subsurface current tracing drifter is the one that is free to drift at the prescribed depth, with no attachments to the sea surface and carried along with the flow trajectory at that depth.

With the availability of satellite-based position-fixing technology, deep drifters with ARGOS radio transmitters have been developed by Rossby and Dorson (1983) to synoptically measure subsurface and abyssal currents. The drifter uses an ARGOS radio transmitter to reveal its pop-up position at the end of a programmed period of submergence, which may last from days to months. When used in clusters, these drifters yield, after prolonged submergence, an ensemble of displacement vectors, each a time-integral of Lagrangian motion. The design sought to have the following characteristics: (1) ability to withstand high hydrostatic pressure; (2) excellent corrosion resistance for long submerged periods; (3) sufficient payload (5 kg); and (4) carry a 400-MHz radio antenna at depth without damage, yet be able to extend out of the water for satisfactory transmission to the ARGOS satellite. This requires (5) adequate surface riding characteristics and (6) low cost in volume production. Glass housings were considered to be superior, primarily for corrosion resistance. Glass spheres were the initial choice, but this led to concerns about sufficient antenna exposure. Thus, the final choice was to use a standard borosilicate glass pipe of the kind widely used in the chemical and pharmaceutical industries.

Although the pipes are only slightly less expensive than spheres for the same payload, the use of penetrators is greatly facilitated by routing them through a metal endplate instead of drilling through glass. Furthermore, glass pipes chosen by Rossby and Dorson (1983) had the following features: a simple, clean, and structurally stable housing with one end rounded, the other end open, through which the electronics package is inserted. A single metal disk sealed with a Teflon gasket completes the enclosure. The metal endplate had a pressure gauge port and one penetrator for the ballast release wire. Layout of the fully assembled subsurface drifter is shown in Figure 6.1i. It weighed 9.9 kg.; 1.7-kg ballast was required for neutral buoyancy. At the surface, the drifter exposed about 0.4 m of its 1.6-m length. Thus the 0.25-m-long antenna inside the glass pipe was fully exposed.

Rossby and Dorson (1983) chose borosilicate glass for the following reasons: (1) There must be no loss of material by corrosion, which would alter the buoyancy over long periods of time; (2) borosilicate glass shows no plastic flow or deformation under stress; (3) glass (especially borosilicates, with their low metal content) is very transparent to electromagnetic radiation; thus, the antenna can be mounted inside, thereby greatly simplifying the integration of the ARGOS transmitter and the drifter; and (4) glass housings have extremely low coefficients of thermal expansion, allowing deployment of the floats for isopycnal operation (Rossby et al., 1982).

Two disadvantages of glass pipes have been identified. First, they are delicate, requiring care in handling. However, the use of robust packaging can compensate for this issue. The other problem is their end closure. The open end of the glass pipe has a conical flange with a rounded end-surface (Figure 6.1ii) with a concentric groove in the middle. In normal use, pipe sections are held together with clamps pulling from the conical flange. In this case, Teflon gaskets provide the seal, and the end surfaces are never subject to high axial loading. In the use of closed pipes as

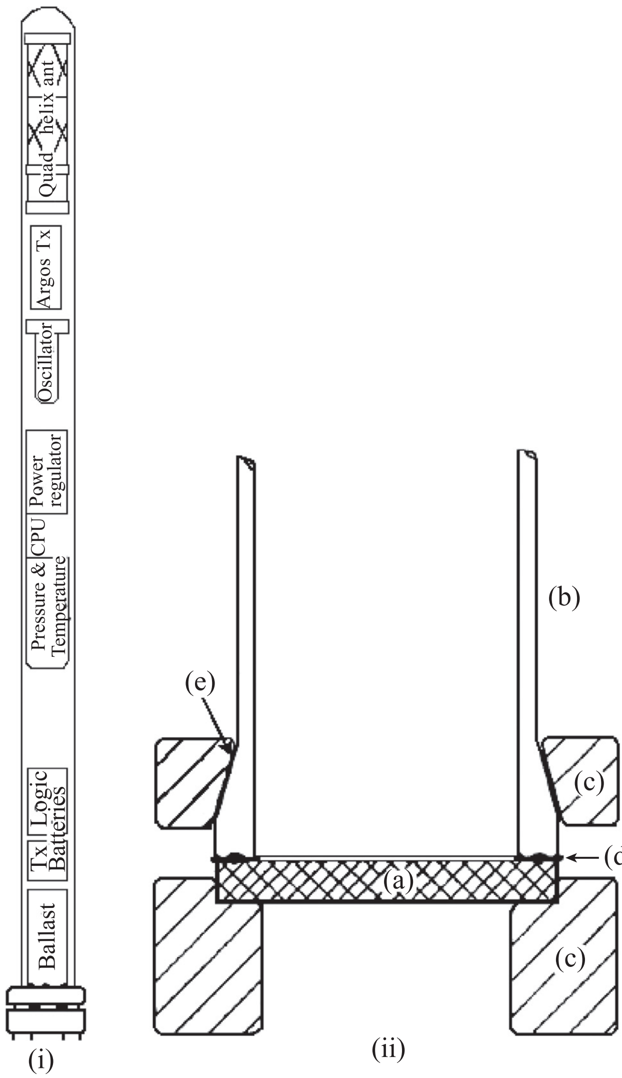

FIGURE 6.1 (i) Layout of the fully assembled subsurface drifter. (ii) Cross-section of glass pipe and endplate assembly. The aluminum endplate (a) is bolted to the glass pipe (b) by means of a polypropylene clamp assembly (c). A Teflon gasket (d) conforms to the shape of the glass end surface to provide a watertight seal. A thin vinyl or rubber pad (e) is fitted to the glass flange. *(Source: Rossby and Dorson, 1983.)*

subsurface drifters, they are subject to large external pressures. Ordinarily this should not matter, because glass is very resistant to compression. The difficulty is that the end surface is not truly flat. Thus, the axial loading from an endplate under high hydrostatic pressure will be nonuniform, both radially and along the perimeter. In light of extensive laboratory studies, it was found that 3-in. glass pipes cannot be reused reliably at pressures exceeding 1,000 psi.

The most serious failure mode of the glass in the flange area is spalling due to tensile stresses in the glass, caused by friction between the glass and the endplate as the glass is compressed. Thus, the choice of gasket material is very important. Rossby and Dorson (1983) found that Teflon acts as an excellent lubricant and, compared to the earlier methods, greatly reduces spalling. In their deployments, the glass flange was prestressed into compression by means of an external clamp or collar (Figure 6.1ii). The arrangement has been reported to be very reliable, rendering it possible to be deployed at greater depths, possibly to 2,000 m. As an additional precaution against leaks, the outside of the gasket was sprayed with an automotive gasket sealant, which seemed to flow readily into all tight spots and to form a sticky, continuous film around the pipe. However, pipes had been sealed many times without the sealant and used at depth with no problems.

At the end of its submergence mission, the microprocessor turns on the ballast circuit. This circuit consists of a transistor that causes a thin wire to dissolve electrolytically and to drop a 2.9-kg ballast weight. The process takes 2 minutes. Thereafter, the instrument ascends at a speed of approximately 2 m/s, so the time to surface ranges up to 30 min, depending on its depth.

As the deep drifter pops up to the surface at the end of a programmed period of submergence, it broadcasts the collected information to the ARGOS satellite. The float starts transmitting 30 min after release. The format for the radio transmission is structured to conform to the RF requirements of the ARGOS system. Approximately every 43 seconds, a message of 32 bytes is transmitted. Thirty of the bytes contain pressure and temperature data; the other two are used for identification and error detection. Forty-eight different messages and a total of 35 min are required to transmit the entire memory. Since a single satellite pass rarely lasts more than 10 to 12 min, a number of passes is required for the entire dataset to be obtained.

The pop-up position of the drifter is determined using the ARGOS satellite-borne relocation system by processing the Doppler shift in the signal transmitted by the ARGOS radio transmitter on the drifter (Briscoe et al., 1987). Subsequent developments in ARGOS-tracked drifter designs permit accurate measurements of mean Lagrangian displacements of water parcels in the mixed layer as well (Niiler et al., 1987).

To sum up, functionally the deep drifter has two operational modes: submerged and surface. While submerged, the instrument is drifting under the influence of the ambient water current velocity, thus providing a Lagrangian view of the oceanic water circulation in its neighborhood. It also makes seawater pressure and temperature measurements on a regular schedule to identify regions of upwelling, fronts, and the like. On the surface, it broadcasts the collected information to the ARGOS system.

Although a satellite-recovered pop-up subsurface drifter has the advantage of not being tied to a surface float, its numerous geographical positions during its current-driven motion between the two successive pop-up positions are unknown. This is a drawback of this method.

6.3. SWALLOW FLOATS TRACKED BY SHIP-BORNE HYDROPHONES

The first successful long-term operating and ideal subsurface water current tracer, the geographical positions of which can be determined at regular intervals—the neutrally buoyancy float—was developed and used by Dr. John Swallow in 1950s; this float began to be known as *Swallow float* after his name. Conceptually, a Swallow float is a neutrally buoyant device with an acoustic transducer that transmits CW pulses according to a precisely timed schedule. The float functions as an acoustic beacon for tremendous distances. In practice, however, a considerable engineering effort is required to create a float with sufficient acoustic range and with an expected life length of 9–12 months. These requirements imposed special demands on reliability, corrosion resistance, efficiency of operation, and conservation of power. Fortunately, the standard Swallow floats were used with great success and operated for as long as seven weeks (Swallow and Hamon, 1960).

In classic isobaric operation, the compressibility of the float must be significantly less than that of the seawater. Thus, the philosophy behind the operation of a Swallow float is that a body that is less compressible than seawater will gain buoyancy as it sinks; and if its excess weight at the surface is small, it may at some depth gain enough to become neutrally buoyant, at which time no further sinking will occur (Swallow, 1955). In isobaric operation, if a float is displaced upward from its equilibrium surface, it will expand less than the water around it. The resulting density difference will force it back to its equilibrium depth. In other words, the Swallow float can be adjusted so that, at a certain depth, the weight of the float equals the weight of the water displaced by it. At this depth, the float remains neutrally buoyant so that it is perfectly free to move with a prevailing horizontal flow of water (Weidemann, 1966; Sturges, 1980; Pickard and Emery, 1982).

The operation of a Swallow float is as follows: After being released from a ship, a float sinks to the selected depth and then drifts horizontally with the water around it. The water-flow trajectory is traced by periodically determining the position of the subsurface float for a sufficiently long period of time (Swallow, 1955). Following the movement of such a float would give a direct measurement of the current at that depth, free from the uncertainties involved in using a conventional current meter from an anchored ship. The possibility of using this method for measuring deep-drift currents over a long period was first suggested by Stommel (1955).

Recovery of the subsurface float after a specified mission requires the use of an expendable ballast weight attached to the bottom end of the float. Ballasting a float means adjusting its weight to neutral buoyancy to a certain depth or for a certain density (σ_t) surface (i.e., isobaric or isopycnal operation). Isobaric floats have been in common use since the pioneering development by John Swallow in the 1950s (Swallow, 1955). Isopycnal studies were initiated in later years (Rossby et al., 1985a).

The problem of locating the neutrally buoyant subsurface drifting float was solved by an ingenious technique of outfitting the float with an acoustic transmitter, known as a *pinger*. In this case, besides having a sufficiently low compressibility, the float must provide enough spare buoyancy to carry this transmitter and must not collapse at the greatest working depth. In the design adopted by Swallow, the acoustic transmitters were capable of sending out a short pulse every few seconds for two or three days. Aluminum alloy scaffold tubing (alloy specification HE-10-WP) has been found to possess the required mechanical properties and can be made into convenient containers for the electrical circuits and batteries. Six meters of such tubing were needed to provide sufficient buoyancy to each float (Figure 6.2), and for ease of handling this tubing was cut into two 3-m lengths laid side by side—one containing the transmitter circuit and batteries and the other providing buoyancy. A simple electronic circuit provided the 10-kHz signal that drove a magnetostrictive nickel scroll sound source, which was wound toroidally and energized by discharging a capacitor through a flash tube. The sound source required for the experiment was available from the Royal Navy. End caps were secured using the then-new O-rings. Properly sealed scaffold tubing has been successfully tested to a 4,500-m depth.

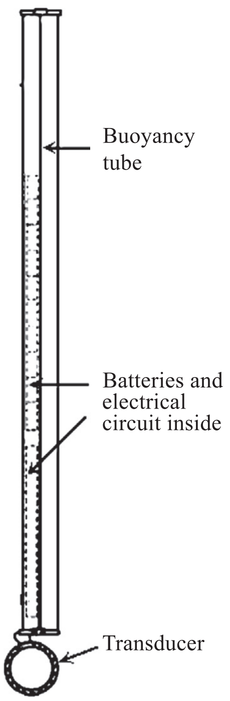

FIGURE 6.2 Sketch of a Swallow float and acoustic transmitter. *(Source: In part from Swallow, 1955.)*

The floats weighed around 10 kg in air but had to be weighed in water so that they could be ballasted to stabilize at their target depth (known as *parking depth*). In the float designed by Swallow (1955), the mean density of each complete float and transmitter was adjusted to an accurately known value by immersing it in a salt solution of known density and temperature and adding weights until it was neutrally buoyant. This adjustment could be made to 1 gm without difficulty, with a float weighing about 10 kg in air. The density could be altered to any desired value by adding or subtracting weights in proportion to the total weight of the float. All the extra weights were put inside the buoyancy tube so that no change in volume had to be allowed for. Before launching any of the floats, temperature and salinity observations were made and the water densities *in situ* calculated from tables (Zubov and Czihirin, 1940). The extra weight required to take the float down to any desired depth could then be determined from the known density at that depth and the calculated compressibility of the float. The floats needed only 38 g of negative buoyancy to stabilize at 1,000 m, so great care was needed with the weighing and density calculations and to eliminate trapped air bubbles.

The method used for tracking the drifting float was to lower two acoustic receivers (known as *hydrophones*) over the sides of a ship, which followed the subsurface drifting float. The two hydrophones were maintained as far apart as possible. The ship track was maneuvered so that the shipborne hydrophone continued to receive the acoustic signals (pings) transmitted by the float-borne pinger and thus tracked the path of the subsurface currents at the depth layer of the drifting float. The acoustic pulses from the neutral buoyancy float will be received at the two spatially separated hydrophones at two different times unless the float's location is just below the ship or at an orientation perpendicular to a plane joining the positions of the two hydrophones. From the magnitude and sign of the observed time difference, it is possible to estimate the bearing of the float with reference to the plane joining the positions of the two hydrophones using known values of the spatial separation between the two hydrophones and the velocity of sound in seawater. To avoid errors in estimation of the bearing of the float, the hydrophones were kept fairly shallow (approximately 7 m below the sea surface) and were weighted to prevent their cables from straying too far from the ship's side. Detection of float position using shipborne hydrophones is schematically shown in Figure 6.3. Because the chasing ship continuously determined its own position by conventional navigational techniques, the speed and trajectory and, therefore, the direction of movement of the current-driven drift of the float at that depth could be determined.

In practice, tracking a drifting subsurface float is more complicated, as indicated in this description given by

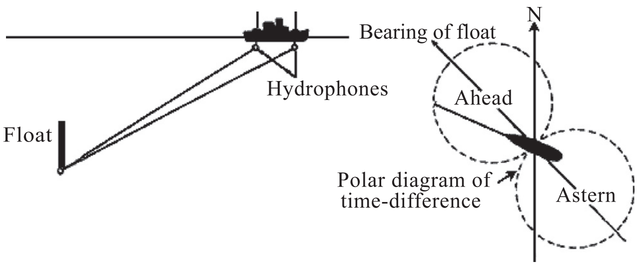

FIGURE 6.3 Method of locating a Swallow float. *(Source: Swallow, 1955.)*

Swallow: With the ship stopped head-to-wind, two hydrophones are lowered over the side, as far apart as can be conveniently arranged. The signals from them are fed via separate tuned amplifiers to a double-beam oscilloscope, the time base of which can be triggered from signals applied to either beam. Pulses from the subsurface drifting transmitter are received at different times at the two hydrophones, and the magnitude and sign of this time difference can be measured on the oscilloscope. As the ship's head falls away from the wind direction, the time difference is observed as a function of the bearing of the line joining the hydrophones. It follows a "figure-eight" polar diagram, with sharp zero values when the bearing is at right angles to the line from the ship's position to the subsurface drifting float. Usually observations over an arc of about 120° are enough to indicate the bearing from the ship to this float. The process is repeated with the ship in other positions, and the intersections of these bearings locate the subsurface float in a horizontal plane. The ship's position is determined by radar range and bearing from an anchored buoy, and the movement of the buoy itself is checked by sounding over small but recognizable nearby features on the sea bed.

Each time a bearing of it is taken, the depth of the subsurface drifting float can be estimated from the size of the "figure-eight" pattern obtained when the time differences are plotted. The ratio of the maximum time difference observed (when the ship is heading directly toward the float) to the direct travel time from one hydrophone to the other is the cosine of the angle between the horizontal and the ray coming from the float to the ship. The depth of the float can then be found when the horizontal distance between it and the ship is known. The direct travel time between hydrophones is measured by floating a transmitter on the surface and observing the maximum time difference at the two hydrophones as the ship is swung round. To avoid errors in bearings and in the time differences, the hydrophones are kept fairly shallow (about 7 m) and are weighted to prevent their cables from straying too far from the ship's side.

The first floats were deployed in June 1955 over the Iberian Abyssal Plain only six months after construction started. The first float was tracked for two and half days by determining its azimuth relative to the ship by using two hydrophones fore and aft and displaying their outputs on a cathode ray oscilloscope as just described. It has to be remembered that at that time, over much of the world's ocean, navigation was by sun and star sights and dead reckoning. (Later on, the availability of LORAN navigation significantly reduced tracking uncertainties). The float could be followed for a period of days or even weeks. Of the six floats deployed, only two worked satisfactorily, but nevertheless the method had been demonstrated, and the results reported by Swallow (1955) were detailed enough to show evidence of tidal variations. As an example, Figure 6.4 shows the temporal sequence of northward and westward movements of a Swallow float deployed near a submarine ridge. A steady drift plus a lunar semidiurnal oscillation has been fitted by least squares to each of these, leaving the residuals shown. Figure 6.5 shows tidal components of

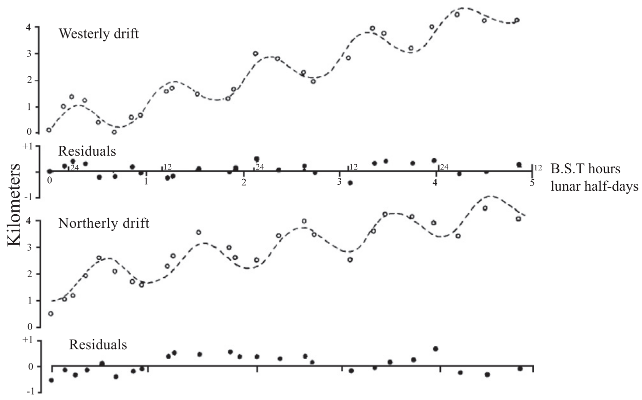

FIGURE 6.4 Temporal sequence of northward and westward movements of a Swallow float deployed near a submarine ridge. *(Source: Swallow, 1955.)*

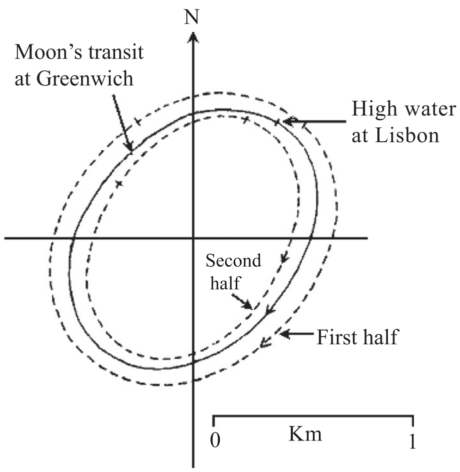

FIGURE 6.5 Tidal components of displacements of a Swallow float combined to form an ellipse. *(Source: Swallow, 1955.)*

displacement combined to form an ellipse. Elaborate deployment of Swallow floats as outlined gave us our first glimpse of the details of deep-water motions and thus contributed significantly to our understanding of several major oceanic subsurface current systems.

While Swallow was engaged in this pioneering development at the National Institute of Oceanography (later renamed the Institute of Oceanographic Sciences) in the United Kingdom, it seems that the neutrally buoyant float concept had also developed quite independently and simultaneously on the other side of the Atlantic (Gould, 2005). Stommel (1955) had called for direct measurement of deep currents and had suggested that it might be done using subsurface neutrally buoyant floats. However, his idea was that they should be tracked through the Sound Fixing and Ranging (SOFAR) channel by the floats creating regular explosions!

According to Gould (2005), at some juncture before 1966, the method of float tracking changed from hydrophones mounted on a ship's hull to two pairs of hydrophones, each pair towed on a cable deployed from the ship's quarter. The "square" of hydrophones separated by about 100 m fore and aft and by the breadth of the ship could be towed at speeds of 3–4 knots (limited by ship noise and hydrodynamic noise) and could determine at what stage a float was abeam of the hydrophone array. This method significantly reduced float-tracking time.

A limitation of Swallow's method is that one ship can follow only a very small number of floats at one time. If several floats are released, e.g., at different depths, it is quite likely that they will perverse and drift off in different directions and the ship will not be able to keep track of them for long. Nevertheless, Swallow floats were really the first oceanographic devices to give us reliable information on the speed and direction of deep currents, and some of the results obtained in this new area have been unexpected. Although several techniques have been proposed for direct measurement of subsurface currents, the most powerful and widely used, perhaps, has been the Swallow float. Further advancements in technology permitted tracking of these neutrally buoyant floats without a ship.

Other than Swallow, only a very small number of researchers used Swallow floats before the late 1960s. Gould (2005) reckons that this was perhaps attributable to a degree of "mystique" about float tracking engendered by Swallow's attention to detail in float preparation and the difficulties of float tracking using low-energy acoustic transmitters. This early limited use of floats contrasts with the larger number of laboratories that were measuring currents using moored instruments at that time. However, because of technological limitations of that era, such as power consumption and data storage capacity, moored current meters were also difficult to use for any period longer than weeks. Consequently, most users were confined to the shelf seas.

6.4. SUBSURFACE FLOATS TRANSMITTING TO MOORED ACOUSTIC RECEIVERS

There are few precise observations of average deep-water motions, primarily because of the limited duration of each experiment. The prevalence of large-velocity fluctuations over short time scales demands long averaging periods before the low-frequency motions with weekly and monthly periods and the net transports can be resolved. Continuous observations over months rather than days would be needed if the mean ocean circulation were to be revealed. Such measurements can, for example, be made with Swallow floats or with current meters, which are designed to operate for months. Both methods are expensive. The latter require two trips to sea, one for their deployment and another for their recovery. A large number of current meters must be distributed in a suitable array if in addition one wants to resolve the spatial structure of the water motions. Such programs are most desirable, but cost considerations, in terms of hardware as well as in ship time, necessarily limit the number and scope of such studies. Similar cost considerations arise in the use of Swallow floats, for which reason these usually cannot be tracked from a surface vessel for longer than perhaps a week. However, the very fact that a Swallow float "tags" and drifts with the water mass makes it ideal for tracing deep-water motions. Thus, if there were a method of locating Swallow floats over long periods of time (months) without the use of a ship, one should hope to obtain, at much less expense, a more accurate estimate of the net drift of the deep waters as well as some information on the character of the water flow, such as, for example, steady, linear, eddy-like motions. It is also interesting to examine what happens as the float approaches or leaves a coastal region.

The prohibitive time factor, expense, and logistical difficulties associated with the method of tracking subsurface floats by ship-borne hydrophones prompted scientists to explore alternate techniques of detection of subsurface drifting floats. M. Ewing's invention of the SOFAR channel during World War II heralded a new era in underwater acoustics, paving the way for development of techniques for making continuous day-by-day measurements of subsurface oceanic currents and their trajectories on a permanent basis. With this development, it was hoped that we should eventually be able to map synoptic charts of currents at various depths in the ocean in the same way as meteorologists keep abreast of the winds. The SOFAR channel permits acoustic signaling over great distances (greater than 1,000 km), provided that the frequency of transmission is low (much smaller than 1,000 Hz). An ingenious method thus evolved for remotely exploring large-scale ocean circulation trajectories is the use of the so-called SOFAR floats. The SOFAR floats are neutrally buoyant subsurface floats that are outfitted with acoustic pingers and released into the oceanic SOFAR channels.

The SOFAR channel, which is an acoustic wave guide, owes its existence to the fact that the speed of sound reaches a minimum value at a certain depth in the ocean. This is because the speed of sound is a function of pressure and temperature (and salinity, to a lesser extent). The speed of sound below the warm surface waters of the ocean decreases with increasing depth due to decreasing temperature. Below the main thermocline, where the thermal gradients become small, the effect of hydrostatic pressure on the speed of sound becomes dominant and thus increases as the depth is further increased. In the western Sargasso Sea, the minimum sound speed is $1{,}492 \pm 2$ m/s and is located at $1{,}200 \pm 200$ meters depth. The accuracy with which a float can be located depends directly on the stability of this minimum.

The significance of the minimum velocity becomes clear when it is realized that sound rays that are radiated within certain angles from the horizontal from a source at the depth of the minimum velocity (the sound channel axis) will be refracted back toward this depth. This acoustic energy, trapped in the vertical, radiates horizontally with a geometric rate of attenuation proportional to $1/R$, where R is the distance, instead of $1/R^2$, as in the case of a spherical radiator. This low rate of attenuation of acoustic signals propagating in the SOFAR channel permits acoustic signals to be detected at great distances from the source. In addition to the geometric attenuation, there is also the frequency-dependent attenuation due to scattering and absorption. Thus, the acoustic signal is attenuated much more rapidly at higher frequencies. For this reason, better reception and greater ranges are obtained by transmitting at as low a frequency as possible. The dual virtues of vertical trapping and low rate of attenuation of acoustic energy in the SOFAR channels permit hydrophones to track the SOFAR floats drifting at far-off distances from the hydrophones.

This application of the SOFAR channel was suggested by H. Stommel (1949, 1955). He suggested that the basic instrument required for this purpose is the oceanographic equivalent of the meteorological constant-altitude balloon: an unmanned subsurface buoy or float, devised so as to float at a nearly constant depth or along an isopleth of temperature or density and equipped with a clockwork designed to drop and/or fire SOFAR charges at certain predetermined times, say once a week, for periods up to half a year. The trajectory of each buoy could be determined from the times of arrival of the explosive sound wave at three SOFAR stations. He predicted that if this method proves feasible, the way will then be clear for a major advance in physical oceanography.

Encouraged by this suggestion, Rossby and Webb (1970) initiated an observational program to study abyssal water motions by tracking subsurface floats that were released in the SOFAR channel, and the first Swallow float was launched in the SOFAR channel in January 1968. These floats are now known as *SOFAR floats*.

SOFAR floats are similar in concept to the original Swallow floats, which have been used with great success. However, the technology for SOFAR floats is much more demanding in terms of reliability, economy of power, batteries with high energy density per unit weight, a low-frequency (preferably less than 500 Hz) acoustic projector with low weight and high efficiency, and corrosion resistance. These special demands of SOFAR floats arise because they act as acoustic beacons for tremendous distances (more than 1,000 km), which must operate over long periods of time (over a year).

Usable acoustic ranges that can be achieved depend largely on ambient acoustic noise. Unfortunately, the ocean is not noiseless. Ships, waves, rainfall, earthquakes—all generate noise in various parts of the frequency spectrum. This imposes a limit on what signals can be detected. Most noise is due to surface agitation, although ships can cause serious interference at frequencies below 400 Hz. According to Rossby and Webb (1970), the sea noise to be expected near Bermuda, Eleuthera, and Puerto Rico in the Atlantic Ocean is largely predictable from knowledge of wind conditions.

It has been found that useful acoustic ranges in excess of 1,000 km are possible for tracking SOFAR floats. In this method, at known time intervals, each float transmits a low-frequency acoustic signal. From the time of arrival of this signal at several widely spaced hydrophones (at ranges of approximately 500 to 1,000 km), the positions of the floats can be determined to within a few kilometers.

The SOFAR floats have been tracked by the use of two receivers separated by a large distance. If the travel times of an acoustic pulse from the SOFAR float to these two receivers are known, then the distance between the float and each receiver can be computed from an *a priori* knowledge of the mean sound velocity in that ocean basin. The position of the float will be one of the two intersection points of the two circles whose centers are the positions of the two receivers and whose radii are the two pulse-travel distances between the float and the two receivers (see Figure 6.6).

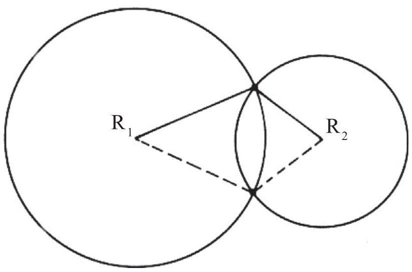

FIGURE 6.6 Method of tracking a SOFAR float with the aid of two acoustic receivers R_1 and R_2.

The ambiguity (i.e., which of the two intersecting points on the two circles represents the true position of the float) can be resolved by knowing its previous location or the location where it was launched. If the pulse-travel time is to be determined precisely, the time of transmission of the acoustic pulse from the float must be known precisely. For this purpose, pulses are transmitted from the float at predetermined times. This means that the clock in the float must be extremely precise. The crystal clocks are known to drift with time. To circumvent this difficulty, three receivers are usually used rather than two. In this case the float position can be determined even if the clock in the float gains or loses time slightly. This is because of the fact that when three receivers are used, the *difference* in time of arrival between two pairs of receivers gives two hyperbolae (on a sphere), the intersection of which is the location of the float (Rossby and Webb, 1970). Because the "difference" in time of arrival is used, any error due to gain or loss of time (which is common to both of the received signals) gets cancelled out. To get sufficient data for this purpose, many pulses (usually a set of 100) are transmitted 1 minute apart every few hours. Because the deep currents are usually small, this methodology of tracking is not expected to give rise to serious errors in the position determination of the float.

In the receiver electronics, some precautions are needed to keep the influence of noise level to a minimum. This is because the acoustic signal traversing a long distance (1,000 km or more in the horizontal) picks up noise in various parts of the frequency spectrum (noise generated by ships, waves, rainfall, earthquakes, and so on). Any slight nonlinearity of the signal amplifiers in the receiver side can generate harmonics, and this will raise the effective noise level of the system. This problem can be minimized by filtering out the noise components in the received signal and amplifying only the frequency band of interest. Usually the received signals are detected in an approximately 1 Hz wide band-pass filter centered at the transmission frequency.

Rossby and Webb (1970) have described an observational program designed to study abyssal water motions in the western Sargasso Sea by tracking Swallow floats in the SOFAR channel. The development of floats that can be tracked by sound transmissions through the SOFAR channel can be traced back to Stommel's original SOFAR concept; but Rossby and Webb (1970) used a low-frequency (500−600 Hz) sound source rather than Stommel's primitive idea of repeated explosions. The prototype SOFAR float constructed by Rossby and Webb (1970) is a tightly engineered Swallow float with an acoustic transducer that transmits CW pulses according to a precisely timed schedule. Their float consisted of a spherical housing (in two hemispheres) of adequate stiffness and resistance to hydrostatic pressure (Figure 6.7). Each hemisphere of the float was spun from aluminum alloy 6061-T6 and had an internal diameter of 0.93 m, a minimum wall thickness of 25 mm, and a hydrostatic collapse safety factor of two or more. All exposed external surfaces were either machined hard anodized aluminum alloy or nonconductive synthetic material. The float enclosed the required power supply and electronic equipment and supported the electroacoustic transducers suspended about 1.5 m beneath it. The electroacoustic transducer was a hollow cylinder of 750 mm diameter, 325 mm length, and 50 mm wall thickness, which vibrated in the fundamental radial mode. The construction was a composite of active barium titanate and passive aluminum alloy in a barrel-stave configuration pre-stressed into compression by circumferential glass fibers in tension and insulated with polyurethane. The electrical connectors to the transducers were protected against fish bite using nylon tubes.

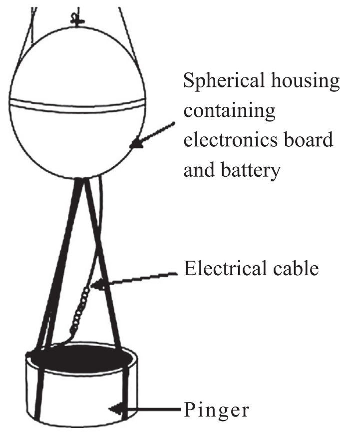

FIGURE 6.7 Prototype SOFAR float. *(Source: Modified from figure 3 of Gould, 2005.)*

The computational method of determining the position of the float is to assume an initial position, the last one, say, and then to calculate the travel times. These are compared to the measured values, and the resulting errors are used to estimate the new position. The process is repeated until the error is negligible. The travel time is estimated from the mean velocity of sound and the range, which is calculated using the Andoyer-Lambert correction for the ellipticity of the Earth.

It may be noted that three major international campaigns—POLYGON, MODE, and POLYMODE—were planned and executed with the hope of better understanding the large-scale circulation features in the Atlantic. POLYGON was led by Leonid Brekhovskikh from the Acoustics Institute, Russia, involving six research vessels and an extensive network of current meters. The current meters were deployed in a pattern resembling the shape of a cross, dubbed the "POLYGON", spanning a region of 113 × 113 nautical miles. This experiment provided some interesting results. It looked as though some large-scale eddy or wave disturbances were travelling across the POLYGON site from east to west. Their scales were close to those of the planetary baroclinic Rossby waves.

Mid-Ocean Dynamics Experiment (MODE) was led by Henry Stommel from the United States. According to Walter Munk, the POLYGON experiment "ignited the mesoscale revolution and that MODE defined the new order" and that "oceanography has never been the same" since. POLYMODE was a combination of the Russian experiment POLYGON and the U.S. led MODE. Russian ships came into Woods Hole during this collaboration. Scripps as well as Woods Hole oceanographic institutions from the United States were involved in this campaign. POLYMODE experiment, led by Andrei Monin, took place in 1978.

The U.S. Air force maintained an array of Missile Impact Location (MIL) hydrophones that located the positions of test missiles that dropped SOFAR charges at the end of their flights. These hydrophones could monitor floats in much of the northwest Atlantic. The first two SOFAR floats were deployed in the Sargasso Sea in 1968 and showed that reception of signals was possible at ranges of up to 1,000 km and that float positions could be determined with accuracy of the order of 3—5 km. The premature failure of both floats after one week and after two days, respectively (they were designed for a life of 9—12 months), was worrisome and attributed to biological attacks on the floats.

The availability of the MIL hydrophones was encouraging to carry out a systematic exploration of the ocean mesoscale over a substantial part of an ocean basin and thus paved the way for planning the 1973 Mid-Ocean Dynamics Experiment (MODE), (MODE Group, 1978). In the MODE experiment, a combination of floats, moored current/temperature recorders, hydrographic surveys, and bottom pressure gauges was used in a nine-month collaborative U.S./U.K. experiment. Because the abrupt failure of both spherical-shaped SOFAR floats after only a few days of operation was a cause for concern, Rossby et al. (1975) adopted an alternate design for use in the MODE experiments at Bermuda triangle. This design was similar to the neutral buoyancy float originally designed by Swallow. The SOFAR floats constructed for MODE (see Figure 6.8) consisted of three cylinders of aluminum alloy.

The central cylinder was 5.2 m long and 30.5 cm in diameter, with hemispherical aluminum end closures, and contained the battery and electronic equipment. The two short cylinders shown in the figure are the low-frequency acoustic transducers, which operate freely flooded. The upper end was open and the acoustic driver, which was a bender plate, was fitted to the lower end. These transducer tubes were mounted on the main housing with four heavy stainless steel studs. All 20 SOFAR floats constructed for MODE were equipped with two acoustic signaling systems: a low-frequency system for long-range shore locations and a high-frequency subsystem for shipboard location and command recovery. A 7.3 kg cylinder of lead was connected to the lower end through an electronically controlled release mechanism and was jettisoned for float recovery on command from the surface. The small, high-frequency (10 kHz) ceramic transducer was connected to the bottom end. All signals were derived from a temperature-compensated quartz crystal oscillator. Electrical energy was furnished by a single battery of 73 kg, 30 volt nominal, and 5 kW hrs. Over 90 percent of the energy was used in the low-frequency signal. The completed float weighed 430 kg. Ballasting was carried out in an enclosure attached to the Woods Hole dock. The floats also had a 10-kHz short-range navigation system to allow their location identification and subsequent recovery by a ship.

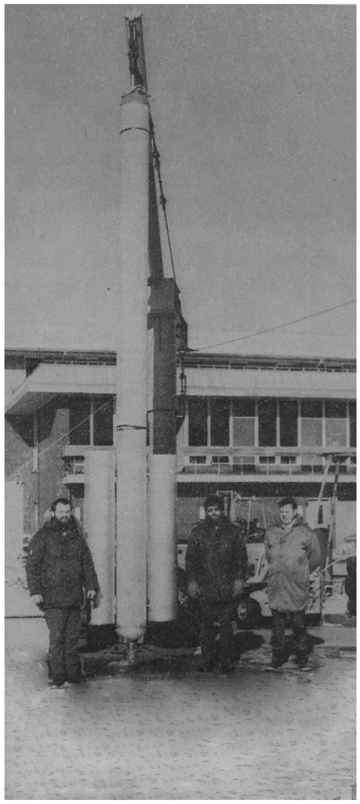

FIGURE 6.8 Photograph of the modified SOFAR float used in the MODE program. *(Source: Rossby et al., 1975. Reproduced with kind permission of Dr. Thomas Rossby.)*

For identification of all 20 floats from the same receiver stations, the method used was to have a combination of one of three carrier frequencies (approximately 267, 270, and 273 Hz) and seven different pulse-repetition rates ranging from 1,437 to 1,443 transmissions per day. These three differing carrier frequencies and seven pulse repetition rates provided 21 channels, which was more than sufficient to track 20 floats. Finally, 20 MODE SOFAR floats, each with a one-year design life, were deployed at a target depth of 1,500 m. The floats were tracked from four widely spaced hydrophone sites (Bermuda, Bahamas, Grand Turk, and Puerto Rico) at ranges of approximately 500 to 1,000 km, as indicated in Figure 6.9. After amplification, filtering,

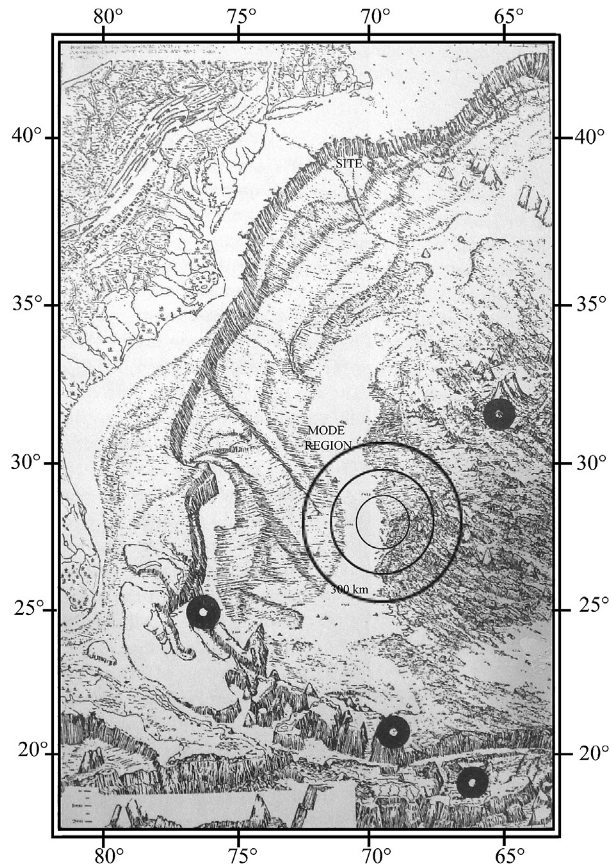

FIGURE 6.9 Physiographic diagram of the western North Atlantic (straddling the rough bottom to the east, the Hatteras Abyssal Plain to the west, and further to the west the Blake-Bahama Outer Ridge), where MODE-I experiment was conducted. The MODE-I region is indicated by three concentric rings of 100, 200, and 300 km radius. The float-monitoring sites are indicated by thick rings. *(Source: Rossby et al., 1975. Reproduced with kind permission of Dr. Thomas Rossby.)*

and addition of timing, the signals were recorded and used for analysis.

The navigational resolution for the trajectory data was typically ±500 m and the accuracy was 2 to 3 km. A good fraction of the error was attributed to the assumption of a “universal” speed of sound of 1,492 m/s throughout the Bermuda triangle, where the MODE experiments were conducted. Trajectories of individual floats, operated at 1,500 m depth in the Bermuda triangle during the MODE experiment, are shown in Figure 6.10. The experiment revealed some new information on the structure and variability of the deep-ocean currents. Some floats remained stationary for a year, whereas others covered hundreds of kilometers. The experiments indicated that the Blake-Bahama Outer Ridge had considerable influence on the organization of the eddy field in the MODE area. Regions of sudden swirls and large horizontal shear were also observed.

The MODE marked a quantum leap in our ability to observe the state of the ocean. Although the experiment

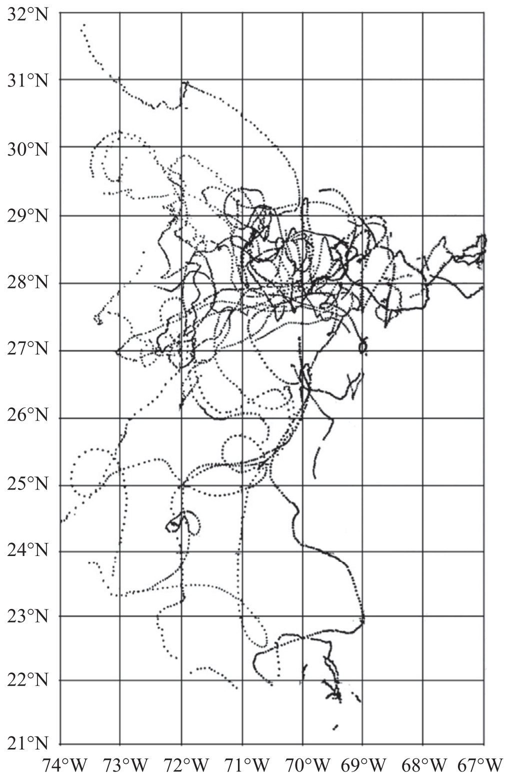

FIGURE 6.10 Trajectories of individual floats, operated at 1,500 m depth in the Bermuda triangle during the MODE experiment (September 28, 1972, to December 31, 1974). *(Source: Rossby et al., 1975. Reproduced with kind permission of Dr. Thomas Rossby.)*

was still primarily ship based, the SOFAR floats enabled day-to-day objective mapping of the ocean mesoscale over an area 400 km square and revealed the long-term propagation of these features (Freeland et al., 1975; Freeland and Gould, 1976). The floats were also entrained into the Gulf Stream rings and were thus able to reveal both their rotation rates and propagation (Cheney et al., 1976).

Since the MODE experiment in spring 1973, acoustically tracked SOFAR floats have been regularly used as Lagrangian drifters to study subsurface currents in the western North Atlantic. By emitting acoustic signals on a regular schedule, their positions have been determined as a function of time at ranges in excess of 2,000 km, depending on acoustic propagation considerations, source power level, and ambient noise conditions. Initially, the use of SOFAR floats was restricted to areas of the western North Atlantic within reach of shore-based SOFAR hydrophones at Bermuda, Eleuthera (Bahamas), Grand Turk Island, and Puerto Rico.

In an alternate design, Webb (1977) used a cylindrical float as part of the POLYMODE programs in a major study of mesoscale circulation in mid-ocean. These floats, although used with no protective coatings, were reported to have performed well even after four years of continuous service. The signals were received at deep hydrophones from moorings and transmitted to land-based stations. A multiple address system using a 1,420 Hz phase-encoded signal transmitted from a recovery ship to the float could establish communication to the float. Upon reply from the float, a recovery command sent from the ship caused the jettison of a 7 kg external ballast weight and initiated a special fast-pressure telemetry cycle to verify release and aid recovery. The jettison was accomplished via a simple electrochemical release. For pickup at sea, a buoyant grapnel tethered to the float by a buoyant line was snared with a heaving line from the ship, and the float was hauled into its launch and recovery frame using the buoyant line.

In the POLYMODE experiments, temperature and pressure were also measured as additional parameters. The measurements were suitably averaged to avoid contamination or aliasing of the data by internal waves. Because early observations revealed a tendency of the floats to sink slowly, approximately 0.5 m/day, apparently due to inelastic creep in the main buoyant housing, adequate precautions were taken in subsequent experiments to prevent such sinking.

To ensure that all the POLYMODE floats drifted over the same isobaric surface, these floats were equipped with a controller that maintained a constant operating pressure. The controller consisted of a block of anode-quality zinc mounted externally in the sea water and could be electrically connected to the main aluminum housing via a switch controlled by the pressure measurement and averaging circuit. The controller works as follows: When the circuit is open, the electrochemical couple is quite inactive. When the circuit is closed, under control of the pressure measurement circuitry, a small saltwater battery is formed. When this happens, zinc goes into solution in the seawater and the whole instrument begins to rise. When the float has risen to the required level, the switch is again opened so that dissolution of zinc is arrested. The regularly telemetered pressure signals indicated that all the POLYMODE floats operated within ± 5 decibar of their normal equilibrium depth. An excellent description of the careful preparations needed before ballasting may be found in Webb (1977). This information will be very useful to those involved in deep-sea circulation measurement using SOFAR floats.

From the mid-1970s, acoustically tracked floats were used extensively to further explore the ocean's mesoscale structure and variability. However, the use of floats was almost entirely applied to the North Atlantic. This bias was the result of the regional interests of the laboratories involved (Woods Hole, University of Rhode Island, and the U.K. Institute of Oceanographic Science) and, of course, the existence of the acoustic tracking network for SOFAR floats. The shorter-range MiniMODE floats were applied to study a number of physical phenomena in detail. In the 1980s SOFAR floats were in extensive use in the eastern North Atlantic in U.S., British, and French oceanographic programs. The SOFAR floats, considering their relatively short development and trial phase, were remarkably successful and, therefore, can be used worldwide.

6.5. SUBSURFACE FLOATS LISTENING TO MOORED ACOUSTIC SOURCES

Subsurface floats transmitting to moored acoustic receivers suffered from several limitations. For example, a close look at its size and its deployment reveals that, to be cost-effective, these floats have to be used in large numbers because the listening stations are rather expensive and require a ship for replacement and final recovery. Second, because of large size and weight, these floats require specialized launching equipment. Although this is not a serious problem for large dedicated studies, it becomes a serious handicap for studies where economy is a concern. Third, although neutrally buoyant Swallow floats and their larger counterparts, SOFAR floats, have been used as subsurface drifters in numerous studies of mesoscale circulation (Swallow, 1955; Rossby et al., 1975; Price and Rossby, 1982) and small-scale motion (Voorhis, 1968; Pochapsky, 1963), these floats approximately track isobaric surfaces and thus are not Lagrangian followers of water parcels in a strict sense. Deviations of Swallow floats and SOFAR floats from true isobaric tracking are due in part to small but finite differences in compressibility and thermal expansion from that of seawater. A better representation of Lagrangian motion, particularly in regions of strong baroclinicity and vertical motion, can be obtained from a Swallow float modified to follow isopycnal rather than isobaric surfaces.

Thus, the requirement for a low-cost, lightweight, and ideal Lagrangian drifter for studies in the Gulf Stream (Rossby et al., 1985a) resulted in the development of a new subsurface float, known as a Ranging and Fixing of Sound (RAFOS) float (Rossby et al., 1986). The RAFOS (SOFAR spelled backward) float is a small, neutrally buoyant subsurface drifter that, like the SOFAR float, uses the deep sound (or SOFAR) channel to determine its position as a function of time. The technical difference between the two systems is that whereas the SOFAR float *transmits* to moored receivers, the RAFOS float *listens* to accurately timed signals from moored sound sources to determine its position. (This difference justifies the use of the backward spelling in naming the float!) Since the RAFOS float is lightweight, making deployment is a simple hand operation, and, in fact, there is no reason why these floats could not be adapted for launch from aircraft.

Isopycnal operation of a subsurface float can be accomplished by the addition of a compressible element, or *compressee* as it is called, which adjusts the effective compressibility of the float package to approximate that of seawater. If the coefficient of thermal expansion of such a float is much smaller than that of seawater, it will remain close to a given isopycnal surface because neither salinity nor temperature changes will affect the density of the float. Hence, it becomes an isopycnal float. In isopycnal operation, no Archemedian restoring force is introduced due to pressure changes, as in the case of the standard Swallow float. For the standard (isobaric) float, the compressibility is typically 30–50 percent less than that of seawater (Rossby et al., 1985b). Consequently, if a float is depressed from its equilibrium depth, it compresses less than the surrounding seawater, gains buoyancy, and thus has a relatively larger restoring force than an equivalent parcel of water. This restoring force maintains the equilibrium depth of the float, which in turn may be affected by the difference in coefficient of thermal expansion of the float and seawater. The compressee consists of a spring-backed piston in a cylinder so that an appropriate volume loss is achieved as a function of pressure (Rossby et al., 1985, 1986).

It must be borne in mind that by using a passive mechanical compressee, isopycnal tracking can only be approximated. This is due to the fact that a system with compressibility that exactly equals that of seawater would still not be a perfect isopycnal follower due to a small but finite coefficient of thermal expansion, although this can be reduced by 30 percent or more by fabricating the compressee from nonmetallic materials. In summary, an isopycnal float can be optimized by matching its compressibility to that of seawater and minimizing its coefficient of thermal expansion as much as possible. In addition, the restoring forces will be maximized and the ballasting errors will be reduced when the float is deployed in a region of strong stratification.

The float used by Rossby and co-researchers in the first test, August 1981, was packaged in a standard 25-cm glass sphere. Two seawater connections drilled through the sphere connected the external 12-kHz acoustic transducer with its power source. Temperature was measured by a thermistor, which was in thermal contact with the sphere wall. It was encoded into a 12-digit binary word, which was transmitted by the transducer every five minutes. The signal was displayed in analog form on the ship's graphic recorder. This binary printout was then read and converted to decimal form. The aluminum compressee consisted of a spring-backed piston set in a cylinder made from solid aluminum stock, with an O-ring set in the piston wall. Thus, unlike the isobaric operation scheme employed in the Swallow float, isopycnal operation is employed in the RAFOS float.

Two preliminary field experiments were conducted in the upper main thermocline near the North Wall of the Gulf Stream. During August 1981, the spherical glass float was deployed near the northern edge of the Gulf Stream (200 km downstream from Cape Hatteras) and was tracked for approximately 100 km. The float, having remained neutrally buoyant in the oxygen minimum zone near 380-m depth, tracked an isopycnal surface as confirmed from CTD data during its passage through a mini-meander. The velocity vectors, based on successive pairs of float positions, showed reasonable values, which compared favorably with the acoustically tracked velocity profiler Pegasus station values for similar depths (see Chapter 10 for a description of Pegasus).

The updated float design (Figure 6.11) used in September 1982 was packaged in a 1.52-m glass pipe with a 7.6-cm nominal ID manufactured by the Corning Glass Co. The RAFOS float is nearly identical to the deep drifter previously developed by Rossby and Dorson (1983). The pipe is made of standard Number 7740 borosilicate glass, which provides the flotation and housing of all electronics. The upper end of the pipe, which floats vertically, is rounded off, and the lower end is sealed with a flat aluminum endplate where all electrical and mechanical penetrators are located. The glass-wall thickness is ~5 mm, giving these pipes a theoretical maximum depth (length/diameter » 1) of ~2,700 m. The internal mechanical assembly consists of a single PVC spar running the length of the pipe. Mounted on it from top to bottom are the radio antenna, the ARGOS transmitter, the microprocessor and memory circuit board, the analog circuit board (pressure, temperature, and acoustic filtering circuits), and at the bottom, for vertical stability, the battery pack. The electronics, flasher, and power packs are

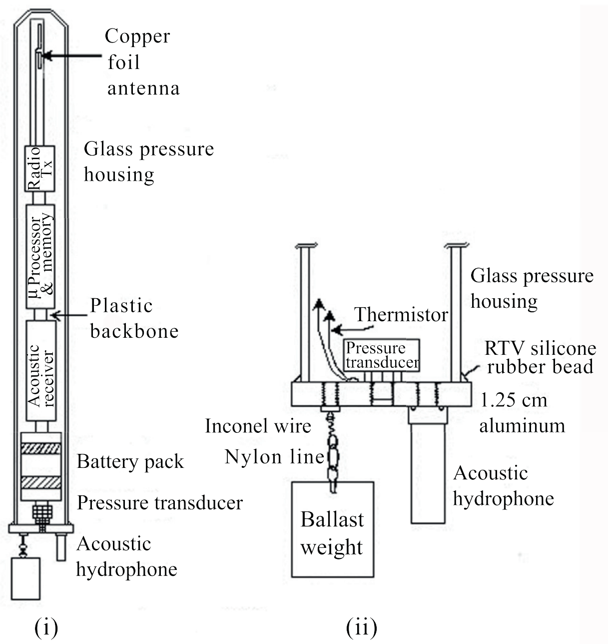

FIGURE 6.11 (i) The mechanical arrangement of the RAFOS float. A glass pipe, rounded at the upper end, is closed at the lower end with an aluminum endplate. All of the components—radio antenna, radio transmitter, microprocessor acoustic receiver, and battery pack—are mounted on a PVC spar prior to insertion in the pipe. (ii) Detailed drawing of the endplate arrangement. *(Source: Rossby et al., 1986, ©American Meteorological Society. Used with permission.)*

seated in foam rubber in order to avoid points of concentrated stress on the inside walls of the glass tube. The batteries are placed at the lower end of the float to facilitate replacement and provide vertical stability, especially at the sea surface. Bolts with washers connecting a polypropylene collar provide sufficient closure to prevent low-pressure leakage. The retrieval bridle is attached to the collar rather than the glass to prevent nonuniform stresses in the glass pipe.

The pressure gauge is rigidly threaded to the endplate and the thermistor is attached to the inside surface. The attachment of the aluminum endplate to the glass pipe is accomplished by applying a bead of silicone rubber around the perimeter where the plate is pressed against the pipe. This is a change from the glass flange-and-clamp arrangement used earlier by Rossby and Dorsan (1983), which was both more expensive and probably less reliable at high pressures. As a precaution, a thin (~0.025 cm) sheet of Teflon is inserted between the flat-ground end surface of the pipe and the endplate, to permit the glass pipe to compress radially under pressure without spalling against the metal surface.

The hard-coat anodized aluminum endplate supports the penetrators for the hydrophone, the ballast release wire, and hole for the pressure gauge. The hydrophone is a single ceramic element and is rigidly potted onto a standard three-pin connector using a two-component polyurethane resin compound. The compressee (see Figure 6.12) used in the 1982 experiment contained a spring-backed piston, with diameter 2.25 cm, set in an aluminum cylinder made of tubing and machined endplates. The cylinder had an outer diameter of 7.57 cm and an overall length of 25.35 cm. The piston was made to protrude approximately 2.54 cm from the endplate to provide better alignment at high pressures and had an O-ring set in the piston wall. The diameter of the piston and the spring constant are adjusted so that the compressibility of the float assembly matches that of seawater. All parts are anodized to minimize saltwater corrosion. Hysteresis due to striction of the piston is reduced by choosing O-rings of high durometer. In subsequent experiments, the closure design was improved by grinding flat the open end of the glass tube and using a very thin Teflon gasket. This greatly reduces the volume change associated with cold flow of the Teflon.

The RAFOS electronics consist of four main parts: a set of sensors for collecting temperature, pressure, and tracking information; an ARGOS-compatible transmitter to relay the collected data after surfacing; a clock for time reference; and a microprocessor (CPU) to control the sensors, store the data, and format the data for the transmitter. The acoustic signal detection and storage of data are all handled by the CMOS microprocessor in the float.

For launching, the 10-kg instrument is lowered to near the water line, the ship is headed up into the current, and floats are released manually. In the absence of the now-ubiquitous GPS position-fixing devices, instrument position was determined from LORAN fixes made while the ship was directly overhead of the float, shown schematically in Figure 6.13. The depth of the float was determined

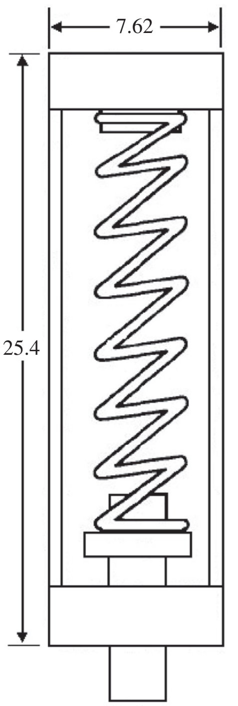

FIGURE 6.12 Schematic diagram of the compressee used in the RAFOS float. *(Source: Rossby et al., 1985.)*

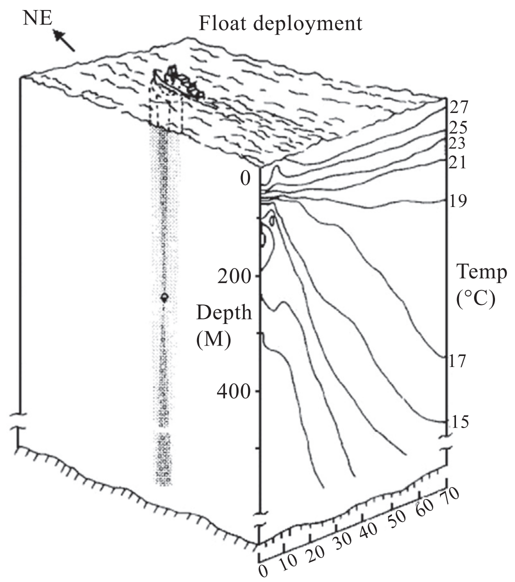

FIGURE 6.13 Schematic diagram of the tracking scenario showing the float, and the direct and bottom-reflected acoustic paths. The upstream temperature section from the August 1981 pilot experiment is also shown. *(Source: Rossby et al., 1985.)*

to an accuracy of 5 m based on the arrival time of the signal reflected from the transducer.

The external ballast (for return to the sea surface) is suspended by a short piece of Inconel wire chosen for its resistance to saltwater corrosion. By dissolving it electrolytically (2 min at 0.3 ampere), the approximately 1-kg ballast is released. A flasher is actuated externally prior to launch and a semi-rigid PVC plastic bridle is used to facilitate recovery. Subsequent to the ballast weight release, the float can be located at the sea surface by the flasher during night, by the brightly colored upper portion during daylight, and by the acoustic signal, which continues to transmit at the surface. Recovery is accomplished by snagging the PVC bridle with boat hooks and lifting it directly on board.

The acquired recorded data are recovered at the end of the mission when the float surfaces and telemeters its memory contents to Systeme Argos, a satellite-borne platform location and data collection system (see Chapter 3). Accordingly, at the preprogrammed end of the mission underwater, the CPU activates a release circuit, which drops a ballast weight, and the float returns to the sea surface. Exactly 30 min after release initiation, under control of the master clock, the ARGOS transmitter in the float starts transmitting the contents of its memory repeatedly to Systeme Argos until the battery in the float is exhausted (a duration of about two weeks). The transmission schedule consists of uploading, approximately every 43 seconds, an ARGOS format message with 32 data bytes. The first byte of each message is a check byte to detect any data errors introduced during transmission and data transfer. The second byte is a message number to keep track of each data block. The remaining 30 bytes are the collected data sequentially transmitted in the order in which they were stored. A satellite pass is within range for less than 15 minutes (there are two satellites), and therefore a number of orbits are required to successfully transfer the complete dataset. Typically, at least three days are required to transfer the 2,835 bytes of data.

All data collected from each 100-min polar orbit are processed at ARGOS headquarters in Toulouse, France, where a few hours later they can be examined via telephone. The data are also forwarded by mail on a regular basis. On calm days at sea, about 90 percent error-free data transfers can be achieved; in severe weather (heavy sea states), this figure can drop to ~50 percent. If necessary, the rejected messages could be examined more closely for salvageable data.

Tracking information is obtained by detecting the time of arrival of SOFAR signals from moored sound sources at the RAFOS float. Just a few sound sources provide navigation for an arbitrary number of floats.

During the September 1982 field experiment, the cylindrical float was tracked for approximately 100 km east of Cape Hatteras. Deployed in the Gulf Stream near the 250-m level was striking evidence that the float was adjusting depth to maintain its prescribed isopycnal surface during a gradual descent and cross-stream motion over the 24-hr sampling period (Rossby et al., 1985). Thus, the float exhibited its isopycnal-following character in both field tests.

Although the use of the SOFAR channel for tracking subsurface floats is quite straightforward, there are several acoustic considerations that should be kept in mind in order to maximize the area of coverage or insonification. These include (Rossby et al., 1986):

- Acoustic source level
- Ambient noise conditions
- Depth of the float in relation to the sound channel axis

Rossby and co-researchers essentially used standard SOFAR floats as acoustic beacons (Webb, 1977). They are buoyed up from the bottom and provide a CW acoustic source level of about 175 dB relative to 1 μPa. The ambient noise conditions are a strong function of weather and shipping. For example, the ambient noise in the Gulf Stream is quite high due to a combination of heavy shipping and strong winds. Despite this fact, useful detection ranges as great as approximately 2,000 km were possible in the Gulf Stream.

Unlike the SOFAR float system, wherein continuous signal monitoring is possible at land-based stations, the RAFOS floats are limited to storing only the two largest correlations per expected signal. Thus, it is necessary to require a large S/N ratio for positive signal detection. It was found that the shallower floats show somewhat poorer performance than the deep floats, but both groups work over the entire listening range of 1,230 km. Cyclonic meanders of the Gulf Stream and/or cold-core rings may cause additional losses.

The procedures for editing and processing the acoustic travel-time data to reconstruct the float trajectories are very similar to those for SOFAR float tracking. To compute the position of the float, the following information is needed (Rossby et al., 1986):

- The time of signal transmission
- The time of arrival of the signal at the float
- The average speed of sound in seawater
- A Doppler correction

The time of transmission is known from the preset transmission schedule for each sound source. The time of signal arrival is determined relative to the float's clock. The float clock is set "on time" and verified (to within a second) at launch, and the accumulated error at the end of its submergence is indicated by the error in radio transmission schedule, which can be determined to a fraction of a second. The biggest uncertainty in the path-averaged speed of sound arises from the fact that the received signal is really a complex signal of many path arrivals spread out over several seconds. Each one of these has a different average speed of sound. However, sophisticated signal identification analysis procedures allow this uncertainty to be minimized to an acceptable level. Doppler correction can be achieved because the transmitted acoustic signal is a linearly ascending CW tone (chirp signal).

The tracking procedure is iterative. In this procedure, a position is assumed (initially, the launch position) and distances to the sound sources are computed. The difference between these and the measured values are used to improve the initial guess. This process is repeated until the absolute sum of the differences is less than 1 km. This position is then used as the initial guess for the next position in time, and so on.

Several RAFOS floats have been launched in the Gulf Stream since the beginning of 1983. An example of the trajectory of a float is shown in Figure 6.14. The three sound sources, indicated by the numerals 1, 2, and 3, are located south of Cape Hatteras, on the northern slope of the Bermuda Seamount and on top of one of the Southern New England seamounts. The trajectory of the float was determined with sound sources 1 and 2 until year-day 74 and with sound sources 2 and 3 thereafter. The trajectory exhibits the characteristic wavy nature of the meandering Gulf Stream. The mean speed of the float (i.e., the traveled distance divided by the elapsed time) is 55 cm/s. A striking aspect of this and all other float tracks was found to be the tendency for floats to shoal from meander trough to crest and to deepen from a meander crest to the next trough. It was observed that during the float's 2,100 km journey to the east, its lateral displacements relative to the current are less than 100 km. From the pressure record it was noticed

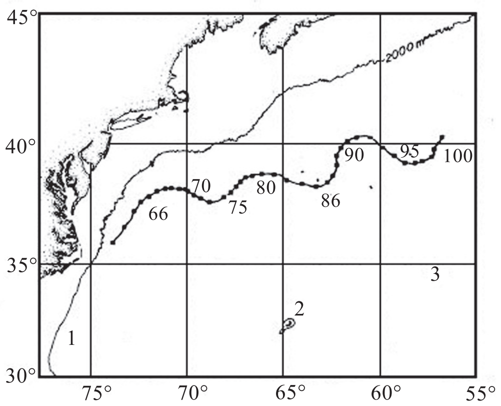

FIGURE 6.14 The 45-day unsmoothed trajectory of a RAFOS float. Elapsed time in year-days (1985) is indicated with one dot per day. The numbers 1, 2, and 3 indicate the locations of the three sound sources. *(Source: Rossby et al., 1986, ©American Meteorological Society. Used with permission.)*

that these motions are not random but clearly a result of the dynamics of curvilinear motion.

It was found that the RAFOS system provides a straightforward means for studying oceanic variability over a wide range of spatial and temporal scales. Sequentially launched in the Gulf Stream, Rossby and co-researchers used these floats to study the space-time evolution of the meandering current. According to them, deployments of dense clusters of floats would enable study of dispersive processes, and when used in concert with hydrographic surveys, these have the potential for unique studies of mixing, entrainment, and topographic effects. Deployed in large numbers over wide areas, they can also be used effectively to estimate mean flows.

The limitations of the single-mission RAFOS floats (acoustic data downloaded only when the float surfaced at the end of its life) were relaxed by development of a multicycle float, the MARVOR (named after the Breton word for a seahorse). MARVOR floats were acoustically tracked but surfaced at regular intervals (typically three months) to transmit the signal arrival times. The process of ascent and descent was achieved by pumping fluid from an internal reservoir to an external bladder (Ollitrault et al., 1994). MARVOR floats were first deployed in 1994 and were used in the South Atlantic SAMBA project and in the Euro float and Arcane projects in the Northeast Atlantic (Gould, 2005).

6.6. ALACE: HORIZONTALLY DISPLACED AND VERTICALLY CYCLING SUBSURFACE FLOAT

Acoustically tracked floats are more logistically efficient when used in dense localized arrays than when providing long records from the widespread low-concentration arrays most appropriate for mapping low-frequency flows. As the number of floats within acoustic range of a single tracking-array element decreases, the fraction of costs devoted to maintaining the tracking array increases.

Motivated by these considerations in exploring large-scale, low-frequency subsurface oceanic currents velocities, Davis et al. (1992) developed a new kind of subsurface float that is autonomous from acoustic tracking networks and is named the Autonomous Lagrangian Circulation Explorer (ALACE, pronounced like Lewis Carroll's Wonderland explorer, Alice). The float periodically increases its buoyancy and rises to the surface, where it is located by the ARGOS satellite system. Subsequently, the float returns to depth to continue water following. ALACE is a subsurface float that cycles vertically from a depth (where it is neutrally buoyant) to the surface where it is located by, and relays data to, System ARGOS satellites. ALACE floats are intended to permit exploration of large-scale, low-frequency currents and to provide repeated vertical profiles of ocean variables. ALACE floats periodically change their buoyancy by pumping hydraulic fluid from an internal reservoir to an external bladder, thereby increasing float volume and buoyancy. Because positioning and data relay are accomplished by satellite, ALACE floats are autonomous of the cumbersome acoustic tracking networks and are suitable for global deployment in arrays of any size. While providing only a sequence of displacements between surfacing intervals, ALACE floats are efficient in gathering the widely spaced long-term observations needed to map large-scale average flow.

The major challenges involved in the design of ALACE are obtaining high-energy efficiency so that long lifetimes are possible and maintaining adequate surface following so that ARGOS transmissions are reliable. The major components of an ALACE float are shown in Figure 6.15. The three major subsystems of an ALACE float are (1) a hydraulic system to adjust buoyancy, (2) a microprocessor to schedule and control various functions, and (3) the ARGOS transmitter and antenna. An expanded schematic description of the hydraulic system is given in Figure 6.16.

Buoyancy changes are accomplished by moving hydraulic oil from the internal reservoir to inflate an external bladder, thereby increasing float volume and buoyancy, or allowing fluid to flow from the bladder back into the internal reservoir. Ascending to the sea surface is achieved by allowing hydraulic fluid to flow from the internal reservoir through a 25-µm filter to a small motor-driven hydraulic pump, which pumps high-pressure fluid through a one-way check valve and into the external bladder. The one-way valve prevents reversed flow of high-pressure fluid back through the pump. Descending to the ocean depth is achieved by opening a latching valve, which allows oil to flow from the external bladder (which is at atmospheric pressure or higher) back into the internal reservoir that is maintained at the float's internal pressure of about 0.7 times the atmospheric pressure. The solenoid-actuated latching valve is closed before pumping is restarted. It uses no electrical power to hold in either position. The hydraulic system is completely sealed by the flexible internal reservoir and the external bladder. The external bladder that receives hydraulic fluid is a Buna-N hemisphere. In the float's minimum volume state, the bladder retracts into a hemispheric cavity of approximately the same radius that is machined into the instrument's lower end cap. High reproducibility of the float's minimum buoyancy (and hence equilibrium depth in the submerged state) is obtained because the bladder retracts smoothly into this hemispheric cavity without forming folds or bubbles between the bladder and the cavity surface. The most difficult problem of avoiding loss of prime in the high-pressure pump, caused by air bubbles in the hydraulic fluid, was solved by the use of pumps with a self-priming option. Cleanliness of the hydraulic system remains important for minimizing pump wear and avoiding malfunctions in the latching valve, which must provide a very low leakage rate when closed against high pressure. With the introduction of the self-priming option, the hydraulic system has proven reliable and robust.

The pressure case is a 1-m-long 6061 T-6 aluminum cylinder with 170-mm diameter and 9.5-mm-thick walls. A complete float has a mass of about 23 kg. The upper end cap

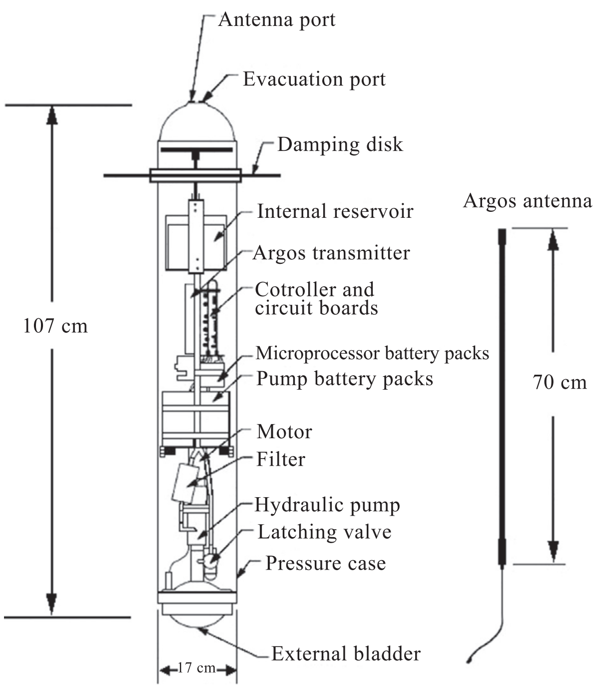

FIGURE 6.15 Schematic of an ALACE float. The antenna shown to the right is mounted on the top hemispherical end cap. *(Source: Davis et al., 1992, ©American Meteorological Society. Used with permission.)*

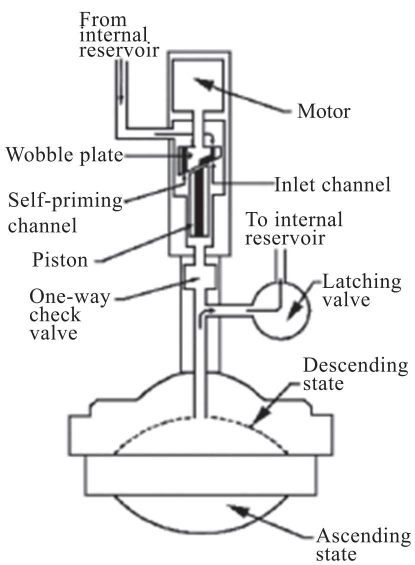

FIGURE 6.16 Expanded schematic of the ALACE hydraulic system. *(Source: Davis et al., 1992, ©American Meteorological Society. Used with permission.)*

is a machined hemisphere (3.8-mm thickness), which in most floats is held in position with epoxy glue, without additional seals. Access to the instrument is through the lower end cap, which forms the hemispheric cavity for the external bladder and is an integral part of the hydraulic subsystem. A plastic disk, of which the diameter is larger than that of the cylindrical float, surrounds the pressure case, perpendicular to the float axis and about 25 cm below the top hemispherical end cap. This disk provides hydrodynamic resistance to relative flow past the float parallel to its axis and damps heaving oscillations when the float is at the surface. This scheme allows the barely buoyant float to follow the wave-disturbed surface and ensures reliable ARGOS communication.

Davis and co-designers of ALACE reckon that a critical component of the instrument is the antenna that must efficiently radiate the 401-MHz ARGOS signal after years of submersion in high-pressure saltwater, dozens of cycles from one to several hundred atmospheres of pressure, and the physical insults of deployment and high sea states. The antenna strength member is a 70-cm-long tapered fiberglass tube that protects the internal radiating element occupying the tube's upper 40 percent. This tube is glued into an aluminum ferrule that screws into the instrument's upper-hemispherical end cap and is sealed with an O-ring. The outside of the fiberglass tube is sealed from the sea by a thermoplastic sheath (shrink tube) bonded to the antenna surface by meltable glue. The electronic and hydraulic components inside the pressure case are mounted to form a single structure that is rigidly attached to the end cap.

The major electronic components include a single-board computer that serves as the ALACE controller, the ARGOS transmitter, and a board for auxiliary functions, such as generating control signals and conditioning analog signals. The microprocessor-based controller's primary function is to schedule all system activities, such as starting the pump motor, opening or closing the latching valve, or starting the ARGOS transmitter. The microprocessor also generates all ARGOS transmitter timing signals and supplies the data message to be transmitted. Reliable ARGOS transmission is critical to achieving the scientific goal of measuring subsurface currents. During operation, when a control function is completed, the microprocessor sets an external programmable alarm clock and puts itself into a low-power dormant state. At the end of the programmed delay, the clock generates a hardware interrupt that wakes up the controller to carry out its next scheduled activity. An internally mounted strain-gauge pressure transducer for which the pressure inlet is exposed to the seawater via a small oil-filled flexible tube mounted on the outside of the end cap measures the submerged depth. An internal thermistor cemented to the lower end cap is used to report at-depth temperature. These data are sent through ARGOS during surfacing of the float.

ALACE is programmed to begin a surfacing cycle by pumping for a specified time, waiting about an hour while the float ascends, and then filling the external bladder to its surface configuration. Typically, about 100 cm^3 more volume than is needed to become neutrally buoyant at the surface is pumped initially, and then the remainder of the internal reservoir's 750-cm^3 capacity is pumped at the surface to provide reserve buoyancy for surface following. The design life of ALACE depends on how far the batteries can be discharged before failing to supply the needed operating voltage.

Due to poor ARGOS satellite coverage, the float positions are not obtained exactly at the surfacing and descent times. This lacuna made it necessary to extrapolate the observed positions to these times. In addition, surface drift must be accurately measured so that measurements of the much slower subsurface motions are not contaminated. Because this requires obtaining as many ARGOS fixes as possible, an important design objective for ALACE was to obtain good surface following so that the ARGOS antenna is rarely submerged. Because ALACE is a float with quasi-linear dynamics, one essential requirement for good surface following is adequate reserve buoyancy. Fortunately, the hydrodynamic resistance to vertical relative flow provided by horizontal damping disks was found to be effective in preventing submergence of the float below the sea surface in the presence of energetic surface waves. Because the reason for good surface following is to make ARGOS communication reliable, the ultimate test of on-surface performance is success in being located by, and sending messages to, Systeme Argos satellites. Quite encouragingly, no connection between wind and either the number of fixes or correct messages could be detected during extensive field trials. It is fortunate that ARGOS communication performance is not influenced by wave state.

Accuracy of subsurface current represented by the subsurface drift of the float, inferred from ARGOS surface fixes, depends on estimating the float positions at the ends of the subsurface sampling period. In addition to extrapolating surface drift to the times of ascent and descent, this depends on rapid transit through shallow regions where current velocities can differ significantly from those at the level of interest. The damping disk used to produce good surface following increases flow resistance and slows vertical motion. Ascent is much more rapid than descent because the buoyant force is intentionally made larger by pumping. On descent, the initial negative buoyancy depends primarily on the equilibrium depth for which the float is ballasted and, to a lesser extent, on the density stratification above that depth. Initial descent is relatively fast, and it takes less than 2 h to reach half the target depth so long as that depth is 2,000 m or less.

A critical element in accurate determination of subsurface drift is extrapolating the observed surface drift to the positions where surfacing first occurs and descent begins. The accuracy

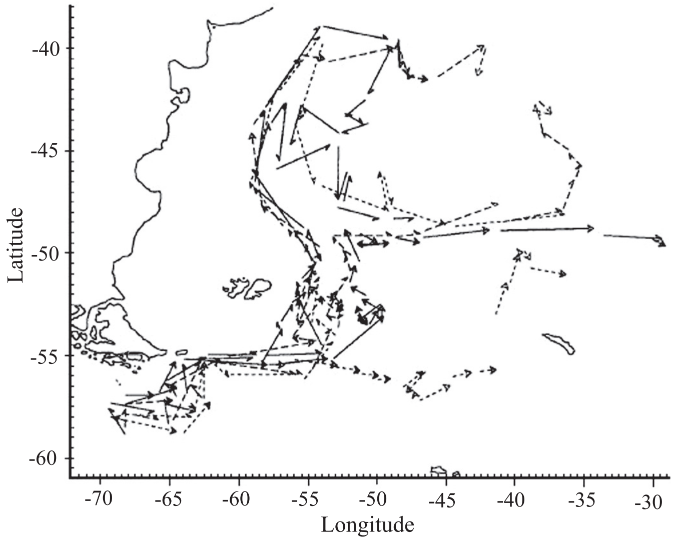

FIGURE 6.17 Displacement vectors from the first year of seven ALACE floats deployed in the Drake Passage. *(Source: Davis et al., 1992, ©American Meteorological Society. Used with permission.)*

with which this can be done depends primarily on the frequency of ARGOS fixes and on the variability of surface currents. Bretherton et al. (1975) used an objective estimation procedure for extrapolation. This procedure is based on treating Lagrangian time series of velocity as samples of an isotropic, stationary random process with known statistics.

After initial field trials in 1988, the first operational use of ALACE floats was carried out in January 1990 for the first World Ocean Circulation Experiment (WOCE) in the Drake Passage (Davis et al., 1996). The floats were ballasted to a nominal depth of 750 m (near the depth of Antarctic intermediate water as it is injected into the South Atlantic) and set to complete a full cycle every 15 days and to remain on the surface for 24 h. The measurements yielded a clear understanding of the circulation route in the region (see Figure 6.17). The WOCE strategy was to make velocity estimates at a common level to provide velocity constraints on the global inverse calculations using hydrography, tracers, and altimetry.

Field experiences have shown that the autonomous float concept is sound and have demonstrated how the data can be used. The potential difficulties in interpretation of data from these floats are (Davis et al., 1992):

1. Trajectory interruptions when the floats rise for satellite locating
2. Uncertainty of the float trajectory between the times it is positioned
3. Contamination of the deep velocity measurements by motion on the surface or during ascent or descent

Fortunately, errors of deep-velocity averages are largely random and much smaller than velocity variability. According to Davis et al. (1992), the procedure of extrapolating surface drift leads to errors of the order 3 km in measuring the displacement between the point at which a float leaves the surface and the point where it resurfaces. The primary contributor to this error is incompletely predictable on-surface motion before the first ARGOS position and after the last fix. These displacement errors correspond to velocity errors of the order 2 mm/s when distributed over the submerged period of 14 days used in Drake Passage and 1 mm/s over the 25-day periods subsequently used in the interior deep ocean. Such errors are largely random because consistent drifts are accurately accounted for by the extrapolation procedure. Developed by Scripps Oceanographic Institute in the mid-1980s and manufactured by Teledyne Webb Research Corporation (WRC), ALACE floats are one of the earlier versions of the floats used in most research today. Although they are still used, there have been improvements in their design.

6.7. DRIFTING PROFILING FLOATS (ARGO FLOATS)

An innovative step initiated in 1999 to take full advantage of the capabilities of drifting profiling floats for prolonged global-scale ocean monitoring gave birth to an international project known as the Array of Real-time Geostrophic Oceanography (Argo). The Argo program was conceived by scientists to greatly improve the collection of observations inside the ocean through increased sampling and increased coverage in terms of time and area via the use of an array of drifting profiling floats known as *Argo floats*. As the name suggests, Argo floats are primarily intended for the study of thermohaline circulation; therefore, apart from drift measurements, temperature, salinity, and pressure are three other essential parameters that are measured by these drifting profiling floats. The drifting and profiling character of the Argo floats allow estimation of geostrophic currents at various depths from repeat profiles of water temperature, salinity, and depth data (density data). Argo's initial aim was to build an array of a real-time, high-resolution monitoring system for upper and middle layers of the world ocean by deploying approximately 3,000 automatic drifting profiling floats, called Argo floats, throughout the ice-free regions of the world ocean, with average spacing of about 300 km.

Three types of drifting instruments that measure ocean temperature and salinity (ALACE, P-ALACE, and SOLO floats) form the backbone of the international Argo program. (P-ALACE is an acronym for Profiling ALACE; SOLO floats are very similar to P-ALACE floats but have better satellite communication and acoustic tracking capabilities). The oceanographic data collected by the Argo floats are primarily intended to understand various oceanographic processes that influence global climate. The original neutrally buoyant floats were designed solely to explore ocean circulation, but Argo floats serve a dual purpose by additionally collecting the CTD profile data. The velocity data from Argo floats have demonstrated enormous potential despite the uncertainties due to their not being acoustically tracked and their departure from being truly Lagrangian due to the time spent at the surface.

As noted in the previous section, Argo floats have the ability to change their own buoyancy, and, when they are deployed, they sink to a prespecified depth, known as *parking depth*. To control the buoyancy of the float, a small amount of oil is contained within it. When the float is submerged, all the oil is kept entirely within the hull. The Argo floats usually remain at the prespecified depth for 7–10 days, drifting with the ambient ocean currents. The float will then rise to the ocean surface, where it communicates its data and position to an orbiting satellite. The float then sinks again, continuing the process. When it is time to rise to the surface, the oil is pumped into an external rubber bladder that expands. Because the weight of the float does not change but its volume increases when the bladder expands, the float becomes more buoyant and ultimately floats to the surface. Similarly, when the float is on the surface and it is time to submerge, the oil is withdrawn from the bladder into the hull of the float and the buoyancy decreases.

Argo floats are built in specialist factories in the United States, France, and Germany. They are built very carefully to work reliably for four years. A float is about 1.1 m tall and weighs around 25 kg. Its body (the pressure case) is made of aluminum tubing sealed at the ends and is strong enough to withstand pressures of more than 200 atmospheres (i.e., the pressure at 2,000 m depth). At the top are the sensors that measure temperature, salinity, and pressure (depth) and an antenna to transmit the data via satellite. At the bottom there is a rubber bladder, which can be deflated to make the float sink or inflated to make it rise under the control of an internal hydraulic system. The pressure case contains electronics, pumps, and many batteries. The electronics include a microprocessor that stores the data from the sensors until it can be transmitted, a program that controls when the float sinks and rises, and a position-fixing and data transmission system that controls the interaction with the satellite. Each float has a unique number that allows it to be recognized and distinguished from all the other floats. Each float is checked carefully before it is launched. The temperature, salinity, and pressure sensors are calibrated in the laboratory to make sure that the measurements made by the float are accurate. All parts of the system are tested to make sure that the float is working properly. Floats are launched from ships doing scientific research, from large container ships, and sometimes even from aircraft. The floats may be lowered into the water from stationary ships, or they may be packaged into deployment boxes, which protect the floats from water impact when they are launched from moving ships or aircraft. Argo has one float on average in every $3^\circ \times 3^\circ$ area of the ocean that is deeper than 2,000 m and not covered by ice. New floats are needed each year to replace old floats that have stopped working.

An Argo float basically drifts at a depth of approximately 1,000 m at which the float's density is the same as the density of the surrounding water and, therefore, it stays at that level, drifting slowly with the ambient currents. It goes down another 1,000 m every 10 days, and then ascends to the surface, measuring temperature and salinity profiles. At the surface, it transmits the observed data to land-based facilities via the ARGOS satellite system and then submerges again to 1,000 m. The Argo float's measurement cycle is repeated every 10 days. After 150–200 repeats (3–4 years), the batteries are exhausted. With no energy to bring it to the surface, the float drifts until the pressure case corrodes and leaks and the float sinks to the sea floor.

The Argo program allowed, for the first time, continuous monitoring of water temperature, salinity, and velocity of the upper ocean, with all data being relayed and made publicly available within hours after collection. This observation system makes possible real-time monitoring of the ocean conditions. This will greatly contribute to the study of interannual, decadal, and interdecadal variations of the climate system, and it will bring substantial improvement in the performance of long-term forecasts.

The first Argo floats were deployed in 2000. As part of the World Ocean Circulation Experiment (WOCE), 306 autonomous floats were deployed in the tropical and South Pacific Ocean and 228 were deployed in the Indian Ocean to observe the basin-wide circulation near 900 m depth. Davis (2005) conducted a comprehensive analysis of the voluminous dataset obtained from Argo floats using various methods such as area averages, local function fits, and a novel application of objective mapping to estimate the mean circulation. By late 2004, over 1,500 neutrally buoyant floats were drifting at depth throughout the global ocean.

They were approximately 50 percent of the final global Argo array that was scheduled for completion by 2007.

By January 2005, more than 1,600 floats were delivering data. By November 2007 the array was 100 percent complete. The project far exceeded the initial target (3,000 floats), and about 5,000 of them were deployed in different parts of the World Oceans by 2012. Besides float deployment, Argo has worked hard to develop two separate datastreams: real time and delayed mode. A real-time data delivery and quality-control system has been established that delivers 90 percent of profiles to users via two global datacenters within 24 hours. A delayed-mode quality-control system (DMQC) has been established, and 60 percent of all eligible profiles have had DMQC applied.

The accuracy of surface currents estimated from Argo floats is constrained by several factors. First, these floats spend only relatively short periods freely drifting at the sea surface (mostly no more than 15 h in the Pacific). Furthermore, their fixes have relatively large errors (150 m, 350 m, or even 1,000 m), and the interval time between the adjacent fixes varies from several minutes to several hours.

Xie and Zhu (2008) reported the development of a new sequential method of Argo float surface trajectory tracking and extrapolating based on the Kalman filter (KF) method, under the presumption that a surface trajectory of Argo float is dominated by a constant current plus inertial oscillation. This trajectory tracking and extrapolating method is claimed to be able to reduce the positioning uncertainties of Argo surface trajectories and provide error estimations. When this method was applied to extrapolate the Argo float positions at the times of float resurfacing and descending, the estimation error of the mid-depth currents could be reduced. Utilizing this method in the Pacific, surface and mid-depth currents were estimated from surface trajectories of Argo floats from 2001 to 2004, along with their detailed error estimations. The average error for surface currents was found to be about 4.4 cm/s, which is equivalent to the accuracy order (5 cm/s) of the Surface Velocity Program drifters. The estimation error of the mid-depth currents at 1,000 db could be reduced to about 0.21 cm/s without considering the effect of vertical shear. The study of Xie and Zhu (2008) showed that the surface trajectory from Argo float provides a new means to measure surface circulations in the global ocean in real time and that the estimated mid-depth current could be one of the important sources in improving the understanding of ocean dynamics.

6.7.1. Profiling Observations from Polar Regions

Because of a lesser amount of observational data in the Arctic Ocean interior, changes of the Arctic Ocean circulation, oceanographic parameters, and sea-ice conditions remained unclear. In addition, there is debate over how changes in the Arctic Ocean are affecting global climate, e.g., as related to the global ocean circulation. Even though the Arctic Ocean plays a critical role in global climate (e.g., Morison et al., 2000; Hassol, 2004), sea ice had previously prohibited Argo float observations in the Arctic Ocean. Instead of such instruments as Argo floats, ice-drifting buoys have been the main method of year-round observation in the Arctic Ocean. Compared to hydrographic surveys of the Arctic Ocean by icebreakers or aircrafts, one of the most important advantages of an ice-drifting buoy is that it can obtain data even in darkness and during severe winter conditions. To provide meteorological and oceanographic observation data throughout the year, the International Arctic Buoy Programme (IABP) maintains a network of ice-drifting buoys (e.g., Rigor et al., 2000).

To monitor and better understand the thermohaline conditions in the ocean interior of the polar regions and thus to elucidate Polar Ocean change, Kikuchi et al. (2007) developed a new Argo-type ocean profiling system. This Polar Ocean Profiling System (POPS) is an ice-drifting buoy system that tethers an Argo-type CTD profiler and is deployed in multiyear ice. JAMSTEC and METOCEAN began collaboration to develop POPS in 2004 with the aim of obtaining oceanographic profiling data from beneath the Arctic ice. POPS consists of an ice platform and a subsurface CTD profiler (see Figure 6.18). It also provides

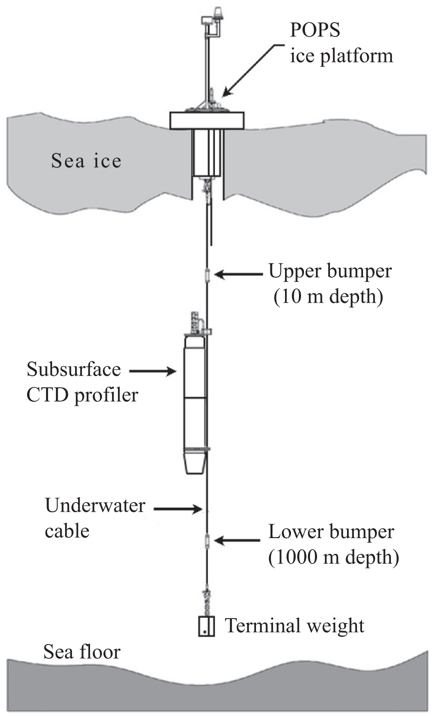

FIGURE 6.18 Schematic view of the Polar Ocean Profiling System (POPS) consisting of an ice platform and a subsurface CTD profiler. *(Source: Kikuchi et al., 2007.)*

meteorological data. Iridium and GPS antennae are located at the top of the meteorological mast, which is placed into a drilled hole in the ice.

The ice platform includes a system controller that manages all data acquisition, processing, formatting, and messaging. The profiler is mounted on an oceanographic cable interfaced to the platform. The profiler moves along the cable between depths of 10 and 1,000 m. The inductive modem system provides data transfer between the ice platform and the profiler. The inductive modem (IM) telemetry system, which includes a Surface Inductive Modem (SIM), an Underwater Inductive Modem (UIM), and two Inductive Cable Couplers (ICCs), is used to establish communication between the ice platform and the subsurface CTD profiler. The SIM is located inside the ice platform, whereas the UIM is inside the profiler. The two ICCs, the plastic-jacketed wire, and the water together make the connection between the SIM and the UIM.

The surface unit power supply consists of two 152-Ah lithium battery packs. The expected lifetime of the ice platform is about 2.68 years for meteorological data acquisition with a GPS position every 3 h and oceanographic profiling data acquisition transferred and processed every three days.

Iridium satellite communication technology sends the observation data and allows remote commands to be sent from the laboratory to the buoy. Data can also be sent to the global telecommunication system (GTS) in real time. Data can easily be accessed from the Argo data server. The system was successfully tested in the Arctic Ocean near the North Pole.

The major difference between POPS and the standard Argo floats is that the POPS profiler is mounted on a cable and slides between a pair of upper and lower bumpers located at 10 and 1,000 m on the cable. The cable is a plastic-impregnated 7 × 7 strand galvanized wire rope. Figure 6.19 shows how the profiler is mounted on the cable.

The upper and lower riders attached to the profiler are carefully designed to minimize friction and drag when the profiler is moving along the cable. In contrast to the original Argo float, the POPS controller software is modified to cope with the nonsurfacing properties and to interface with the IM system (UIM and ICC) to communicate with the ice platform. Its functions include maintenance of the calendar and internal clock, supervision of the depth cycling process, and activation and control of the hydraulic system.

In addition to the 37-kg weight of the 1,000-m cable itself, a 20-kg terminal weight is used to keep the cable as vertical as possible. Although all these calculations allow full data point collection, much faster ice motion will result in missing data due to tilting of the cable. Placing a heavier terminal weight at the end of the cable is possible in order to minimize the risk of missing data points.

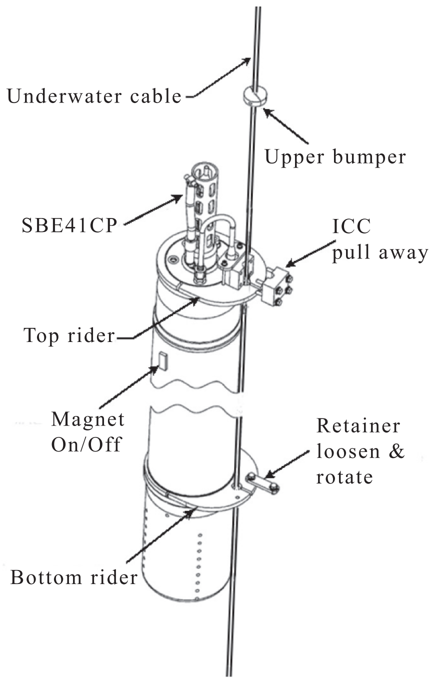

FIGURE 6.19 Sketch of the subsurface CTD profiler and the attachments of the Polar Ocean Profiling System. *(Source: Kikuchi et al., 2007.)*

The total weight of the POPS (ice platform, profiler, cable, and 20-kg terminal weight) is less than 150 kg in air. Therefore, not only a big icebreaker but also a small airplane or helicopter allows accessing the target sites for the POPS deployment on the Arctic multiyear ice. Because of the presence of sea ice, it is necessary to drill a hole through the ice for the POPS deployment. A 10-in. (25.4 cm) diameter hole is enough to put the terminal weight, profiler, and cable into the seawater.

When the profiler has reached and is stabilized at its parking depth, it will establish communication with the platform. The profiler travels at approximately 8−10 cm/s in ascent while traveling at approximately 5 cm/s in descent. The parking and maximum profiling depths are set to 300 and 1,000 m, respectively. This bidirectional communication system provides the users with flexibility and control of the observation after the deployment. For example, it is possible to fine-tune these parameters for optimum performance of the system when ice condition warrants closer attention.

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