3. AUTONOMOUS BUOYANCY-DRIVEN UNDERWATER GLIDERS

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3.1 INTRODUCTION

Historically, the interior ocean has been mainly observed using instruments lowered from research ships or, later, suspended from moorings. Typical ship cruises last a month or two while moorings may last a year or two. The relatively high cost of these observation platforms has limited their number and, consequently, the spatial and temporal density at which the ocean has been observed. Initially this may not have seemed a serious hindrance because the ocean's circulation was thought to be largely steady with broad spatial scales outside a few concentrated boundary currents. Over the last 30 years, however, satellite remote sensing and intensive experimental ocean observations have belied this view and shown that the ocean is highly variable on time scales that are somewhat longer than those of the atmosphere and space scales of tens of kilometers, much smaller than those of the atmosphere. Even before the fullness of ocean variability was known, Stommel (1955) likened the oceanographic observational approach to meteorologists observing the atmosphere using "half a dozen automobiles and kites to which air sounding instruments were attached and doing all their work on dark moonless nights when they could not see what was happening in their medium."

The advent of satellite navigation and communication made possible a class of small, inexpensive instrument platforms that are changing the way the ocean is observed. Much as satellite remote sensing led to a quantum jump in our understanding of the ocean's surface, these new platforms provide a view of the interior ocean with much higher spatial and temporal resolution than is possible with conventional shipboard and moored instruments. Increased resolution is important in solving problems from the management of coastal resources to the prediction of climate change. Surface drifters are now mapping the changing surface circulation and reporting global sea surface temperatures as they vary on mesoscale and climatic time scales (Niiler, 2001). Autonomous profiling floats (Davis *et al.*, 1991) have already shown an ability to return routine real-time observations from all parts of the ice-free ocean at a low cost made possible by minimal dependence on research vessels. The international Argo program (Wilson, 2000) is now building up a global array of 3000 profiling floats, each of which will report an ocean profile every 10 days providing a synoptic view of the ocean much as the World Weather Watch provides global weather information. A feature of both surface drifters and profiling floats is that they drift with the ocean currents, allowing the reliable measurement of these currents but making the location of these measurements uncontrollable and difficult to predict.

Even before the first autonomous floats were operating, Stommel (1989) envisioned a world ocean observing system based on "a fleet of small neutrally-buoyant floats called Slocums" that "migrate vertically through the ocean by changing ballast, and they can be steered horizontally by gliding on wings at about a 35 degrees angle . . . During brief moments at the surface, they transmit their accumulated data and receive instructions . . . Their speed is generally about 0.5 knot." This chapter describes a class of autonomous underwater vehicles (AUVs) that are realizing Stommel's vision. Because they can be constructed for the cost of a few days ship time, can be reused, are light enough to be handled from small boats, can operate for a year or more while covering thousands of kilometers, and report measurements almost immediately while being directed from shore, these vehicles can make subsurface ocean observations at a fraction of the costs of conventional instrument platforms. This cost reduction makes feasible a proliferation of instruments to substantially increase spatial and temporal density of ocean observations and, consequently, the range of scales that can be resolved.

The vehicles described here, autonomous underwater gliders, change their volume and buoyancy to cycle vertically in the ocean and use lift on wings to convert this vertical velocity into forward motion. Wing-lift drives forward motion both as the vehicles ascend and descend, so they follow sawtooth paths. The shallowest points on the sawtooth are at the surface where satellite navigation and communication are carried out, eliminating the need for *in-situ* tracking networks. Four basic sampling modes for gliders have presented themselves. If forward motion is used to counter ambient currents and maintain position, gliders can sample virtually as a vertical array of moored instruments with a single sensor package. Moving from place to place yields a highly resolved section, although the slowness of advance mixes time and spatial variability. Gliders controlled remotely from a research vessel can form an array to describe the spatial and temporal context in which intensive shipboard measurements were embedded. Finally, the long operating lives and ability to sample densely suit gliders to missions where unusual events are sought and then studied intensely when found. With ranges of thousands of kilometers, durations of O (year), and control and global data relay through satellite many new missions are anticipated.

This class of vehicles is distinguished by four inter-related operating characteristics: the use of buoyancy propulsion, a sawtooth operating pattern, long duration, and relatively slow operating speeds. At a fundamental level, generating forward motion from wings is similar to propulsion by propellor thrust. In gliders, electric or thermal energy is converted to pressure–volume work to change vehicle volume and generate relative motion that is converted to forward thrust by wing lift. In propellor vehicles, internal energy is converted to shaft rotation that provides the relative motion so that propellor blades can generate lift and vehicle propulsion thrust. Buoyancy propulsion is well suited to the performance objectives of this class of vehicle. It provides the vertical sampling needed in the stratified ocean where variability along a horizontal path often results mainly from vertical migration of patterns. Typical glide slopes, of the order 1:4, are much steeper than the slope of oceanic distributions, so each leg of a glider sawtooth produces the equivalent of an ocean profile. As Stommel envisioned, a primary objective of gliders is to observe ocean variability, which spans the energetic time scales from days to seasons that characterize meteorologically forced, mesoscale, and interannual variability. This demands operational lifetimes of months that require efficient conversion of energy to motion and minimization of hydrodynamic drag. Much of AUV drag is caused by forward motion of the hull and can be minimized only by streamlining and operating at slow speeds. The significant drag associated with lift can be reduced by using long, slender wings (or propellor blades) with high lift-to-drag ratios (see Chapter 7). While the high power-to-volume ratios needed for high speeds are easier to achieve with propellor systems, high lift-to-drag and high efficiency is more easily achieved in the simpler hydrodynamic environment of wings.

The underwater gliders discussed here were designed to fit into a particular sampling niche. They are small enough to be handled by a crew of 1–3 on small boats without the power assistance generally available on research or survey vessels. They are inexpensive enough that individual projects might afford several – this translates to construction costs equal to that of a very few days of research ship time or a small mooring. They can sample frequently enough to resolve phenomena such as internal waves, fronts, the diurnal cycle, coastal variability and biological patchiness – spanning depth ranges of O (1 km) in a few hours requires vertical speeds of O $(0.1\,\mathrm{m\,s^{-1}})$. Collecting long time series is made feasible by amortizing the costs of deployment/recovery over long operational durations of O (year). A high operating speed would, of course, be desirable, but this conflicts with the primary goals of low cost, small size and long duration. Yet, if gliders are to maintain station or occupy prescribed sections they must have operating speeds that are at least comparable to typical sustained large-scale currents averaged over the glider's operating depth. Localized currents may exceed $1\,\mathrm{m\,s^{-1}}$ while currents of O $(0.2\,\mathrm{m\,s^{-1}})$ are common. Depth-averaged currents are generally weaker than surface currents and gliders can operate in localized strong currents by drifting downstream as they cross and then make up lost ground in parallel regions of weak flow. Nevertheless, long periods operating at O $(0.2\,\mathrm{m\,s^{-1}})$ are needed and higher peak speeds would expand the operating area. Accurate on-surface navigation, the ability to accept simple commands from shore and to relay kilobytes of data to shore, reliable control of gliding performance and the ability to process data *in situ* were additional design requirements.

The functional design goals roughly translate to:

- endurance of O (year) at operating speeds of O $(0.2\,\mathrm{m\,s^{-1}})$ and vertical velocities of O $(0.1\,\mathrm{m\,s^{-1}})$;
- mass of O (50 kg), length of O (2 m), and maximum operating depths from O (100 m) to O (1,000 m);
- GPS navigation, an ability to receive simple commands and transmit kilobytes per day of data, and PC-level internal data processing; and
- construction cost of O ($50,000) and refueling cost of O ($3,000).

The technology developed to meet these objectives is very new. In Section 2, we describe four field-tested gliders, none of which was operational much before the year 2000. Each glider embodies a particular set of solutions to the major design challenges and evaluation of these solutions is not yet complete. It is likely that different combinations of features will appear in future vehicles. For this reason, the discussion in Section 3 focuses on specific design challenges and comparison of how they have been addressed. Section 4 describes observations from a few glider operations to give a flavor for what can be accomplished. This chapter concludes with some thoughts on suitable sensors and the future.

3.2 THE GLIDERS OF 2001

Twenty years after Stommel's futuristic article anticipating Slocums (named for Joshua Slocum, the first solo global circumnavigator), there exist three ocean-proven electric-powered gliders and a field-tested thermal-powered glider. The University of Washington (UW) "Seaglider" and Scripps Institution of Oceanography (SIO) "Spray" (Joshua Slocum's boat was named "Spray") are electric-powered vehicles optimized for use in the deep ocean where long duration is paramount. Webb Research Corp (WRC) optimized "Slocum Battery" for missions in shallow coastal environments and "Slocum Thermal" for long duration missions in waters with a well-developed thermocline.

3.2.1 Spray and Slocum Battery

Slocum Battery (Webb *et al.*, 2001) and Spray (Sherman *et al.*, 2001) are the simplest gliders described here. Both employ battery-powered buoyancy engines and aluminium pressure hulls that are shaped for low hydrodynamic drag. Figure 3.1 shows Slocum and the forces involved in gliding. Figure 3.6 is a photograph of Slocum. Spray is shown in Figures 3.2 and 3.3.

Slocum Battery is optimized for shallow-water coastal operation, where rapid turning and vertical velocity changes are needed. It has a shallow pressure rating and uses a large-volume single-stroke pump to push water in and out of a port in the nose for rapid volume control. This pump is more efficient in shallow operation than are the pumps designed for deep operation. Primary pitch control is achieved by the movement of water for buoyancy control and pitch is trimmed by moving internal mass. An operable rudder controls the turning rate while maintaining a level attitude for an acoustic altimeter. Antennas are housed in a vertical stabilizer that is raised above the surface when the vehicle is pitched forward for navigation or communication. Pitch moment and surface buoyancy are augmented by inflating an airbladder at the surface. Sensors are mounted in a modular center payload bay.

Spray is optimized for long-duration, long-range, and deep-ocean use where the emphasis is on energy efficiency. The hull employs a finer entry shape than the Slocum Battery glider hull, which has about 50% higher drag (Sherman *et al.*, 2001). Spray employs a high-pressure wobble-plate reciprocating pump and external bladders in the same hydraulic configuration as ALACE floats (Davis *et al.*, 1991). GPS and satellite communication antennas are housed in a wing that is rolled vertical during navigation and communication. The vertical stabilizer houses an emergency-recovery antenna. Scientific sensors may be mounted on the hull (as is the CTD in Figure 3.2) or aft of the pressure hull in the flooded compartment that supports the vertical stabilizer. Extra room for sensors can be obtained by lengthening this compartment.

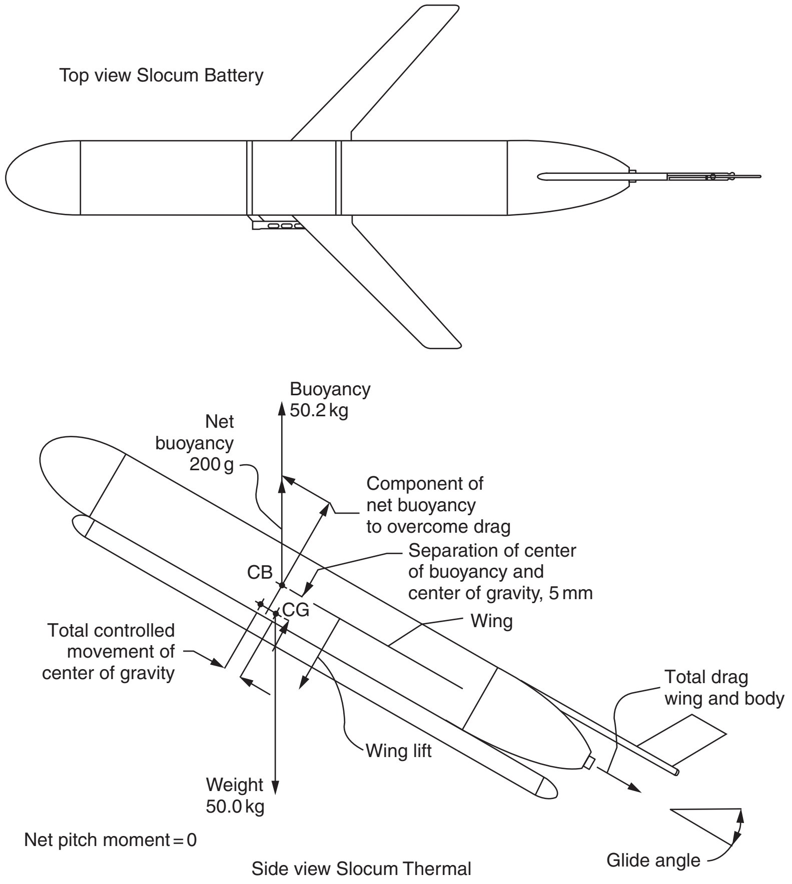

Figure 3.1 Top view is of Slocum Battery showing placement of a un-pumped CTD and the modular center payload bay. Side view is of Slocum Thermal showing the forces involved in gliding upwards, which applies to all gliders. Tubes below the Thermal model are the heat exchangers that drive the vehicle's thermodynamic propulsion cycle.

Glide control in Spray is achieved exclusively by axial translation and rotation of internal battery packs. Pitch is controlled simply by moving the center of gravity in the manner of a hang glider. Turning is initiated by rolling. This gives the lift vector a horizontal component and induces vehicle sideslip in the plane of the wing in the direction of the buoyant force. The horizontal component of lift provides the centripetal force for turning while sideslip acting on the vertical stabilizer produces the yaw moment needed to change vehicle heading. For example, to turn right during descent the right wing is dropped, like a conventional airplane, generating a lift component to the right that drives the vehicle to the right. Sideslips down and to the right acts on the vertical stabilizer causing the nose to yaw to the right. To turn right in ascent the glider is rolled oppositely by dropping the left wing.

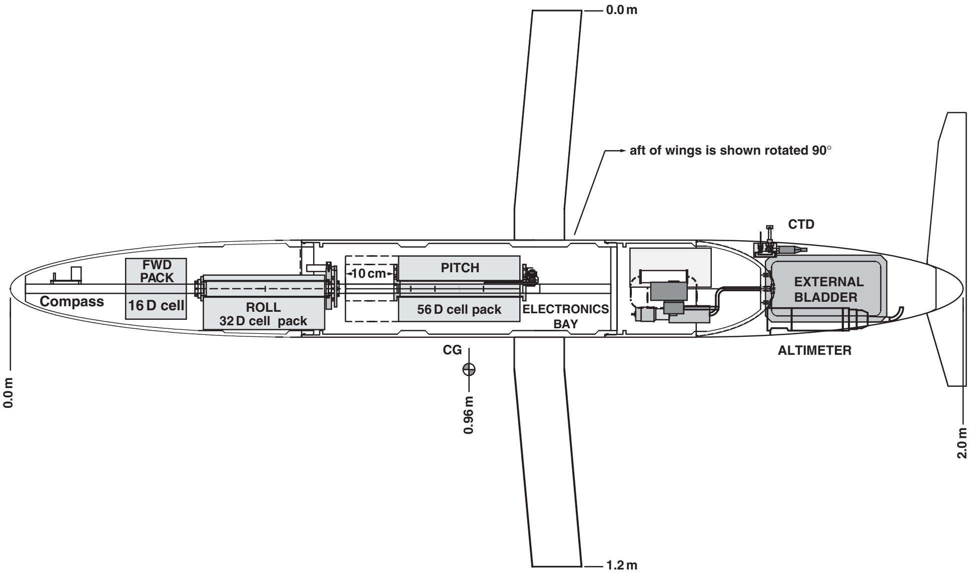

Figure 3.2 Schematic of Spray. Forward of the wings is a top view, aft is a view from the port side. The hull is three pieces. Separate battery packs are moved to control pitch and roll. Antennas are enclosed in a wing that is rolled vertical on the surface. An aft flooded section houses hydraulic bladders and some science sensors.

Figure 3.3 Spray being loaded onto a small boat in preparation for deployment. The aft flooded bay has been uncovered, exposing the hydraulic bladders. Above and forward of this a small protective covering obscures view of the Precision Measurement Engineering CTD.

3.2.2 Seaglider

Design of the battery-powered Seaglider (Eriksen *et al.*, 2001) emphasized efficient energy use to enable missions of one-year duration and ocean-basin ranges. Seaglider is enclosed in a hydrodynamic fibreglass fairing supporting wings, a vertical stabilizer and trailing antenna staff (Figures 3.4 and 3.5). The shroud is a low-drag hydrodynamic shape, with a maximum diameter at 70% of the body length from the nose, a shape that retains a laminar boundary layer forward of this maximum-diameter point. Form drag is proportional to speed to the $\frac{3}{2}$ power rather than the usual quadratic drag.

The fairing encloses a pressure hull with compressibility similar to that of seawater so that buoyant driving force is not lost as the vehicle changes depth. To achieve neutral compressibility, the hull is comprised of a series of deflecting arched panels supported by ring stiffeners. Compared with a conventional stiffer hull, a neutrally compressible hull can save pumping well over 100 cm^3 at the bottom of a 1,000 m dive. The associated energy saving increases as dive depth squared. Seaglider efficiently maintains position in weak currents by pitching to near vertical and using minimal buoyancy forcing.

Seaglider buoyancy control is provided by a hydraulic system of the ALACE type. Movement of internal masses controls gliding and pitches the vehicle forward to raise the trailing antenna mast during communication and navigation. The wing is so far aft that the turning dynamics are opposite that of Spray. In descent, to turn right the vehicle's left wing is dropped so that lift on the wing drives the stern to left, overcoming lift off the vertical stabilizer, and initiating a turn to the right. Hydrodynamic lift on

Figure 3.4 A Seaglider recovered aboard an inflatable boat after one month in Possession Sound. An un-pumped Sea Bird Electronics conductivity cell (with plastic tubing connected) is mounted above the wing. The antenna at the end of the trailing mast is not in view.

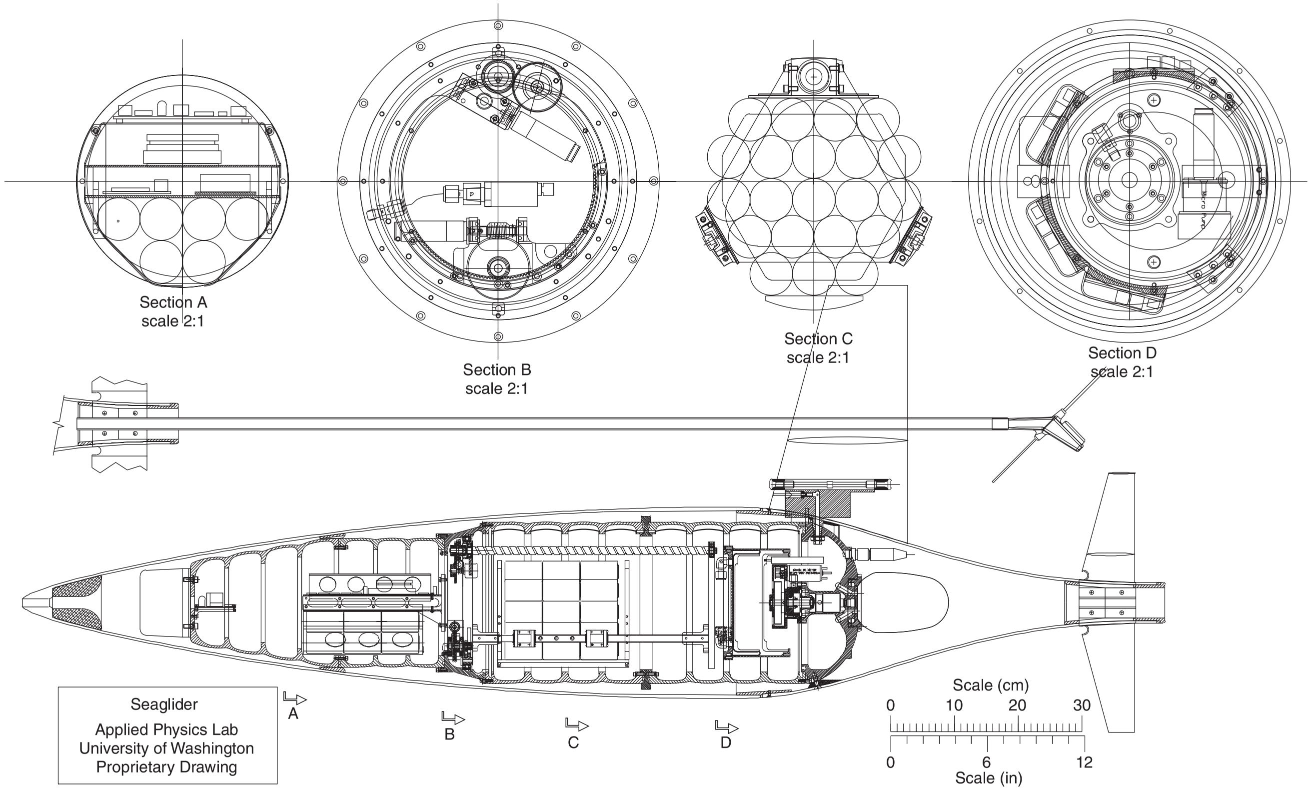

Figure 3.5 Schematic of Seaglider including (from top to bottom) hull cross-sections, the antenna mast, the wing plan-form and cross-section, side view of the hull, and a scale.

the sideslipping hull produces the centripetal force to curve the course. Conversely, in ascent a roll to the left produces a left turn.

3.2.3 Slocum Thermal

Stommel's Slocum concept envisioned a glider harvesting the energy needed for its propulsion from the ocean's temperature gradient. This concept is embodied in Slocum Thermal depicted in Figures 3.1 and 3.6. In missions with electric-powered gliders, 60–85% of the energy consumed goes into propulsion, so a thermal-powered glider may have a range 3–4 times that of a similar electric-powered vehicle. Except for its thermal buoyancy system and using roll rather than a movable rudder to control turning, Slocum Thermal is nearly identical to Slocum Battery. This Slocum's wing is far enough aft that it turns, as does Seaglider, oppositely from Spray and conventional aircraft.

Slocum Thermal propulsion depends on the volume change associated with melting a material with a freezing point in the range of ocean temperatures. As Figure 3.7 describes, in warm surface waters the working fluid is heated, melts, and expands. This expansion compresses an accumulator where energy is stored. Descent is initiated by transferring fluid from an external bladder to an internal reservoir. At temperatures colder than freezing, the freezing contraction draws fluid out of the internal reservoir into the heat exchanger. For ascent, energy stored in the accumulator does the pressure–volume work and the cycle repeats. The heat exchange volume is inside tubes that run the vehicle's length (see Figures 3.1 and 3.6) and provide a large surface area for rapid heat flow.

While Slocum Thermal has yet to complete a long mission at sea, a thermally powered autonomous profiling float completed 120 profiles to over 1250 m over 240 days (Webb, 1999) and Slocum Thermal has operated autonomously in Lake Seneca, New York.

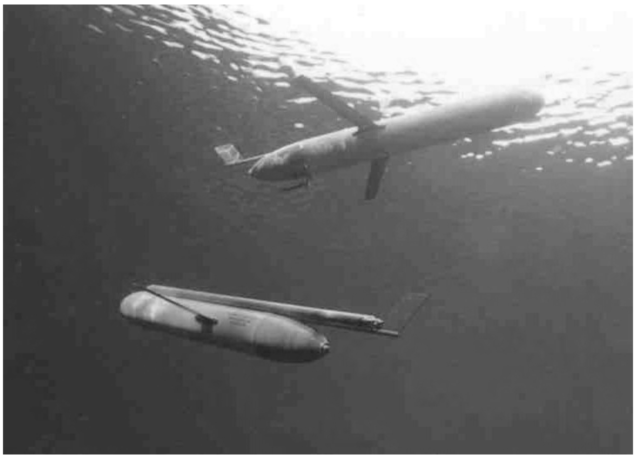

Figure 3.6 Photographs of both Slocum Battery (above) and Slocum Thermal (below). *See* Color Plate 3.

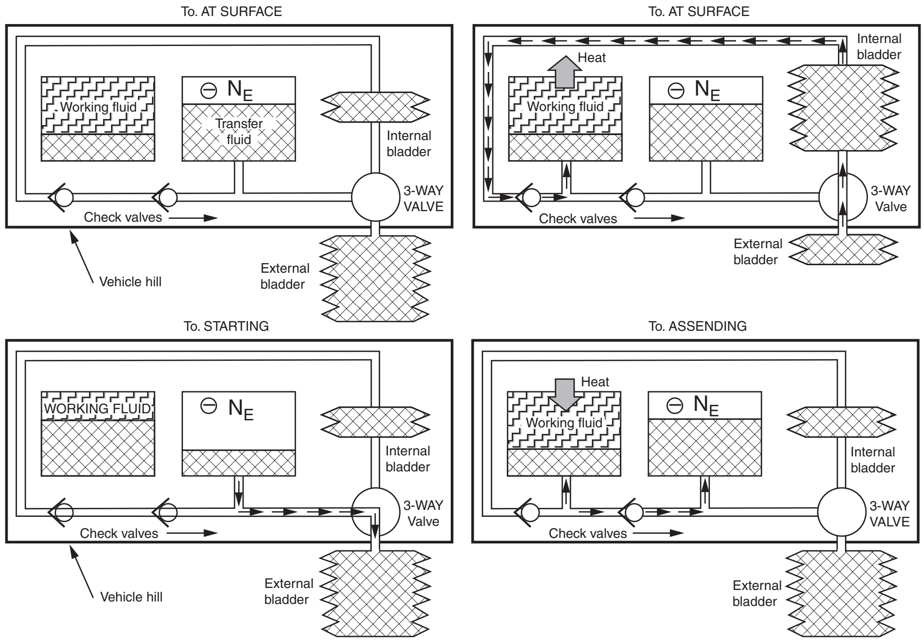

Figure 3.7 The thermodynamic cycle that powers Slocum. The left box is the heat exchange volume and the heat flow is shown with arrows. The middle box is a nitrogen-backed accumulator to store mechanical energy. The cycle is controlled by the three-way valve.

3.2.4 Operating Characteristics

Salient physical and operating characteristics of the four gliders are shown in the Tables 3.1–3.4, where *U* denotes horizontal velocity, *W* denotes vertical velocity and “Payload” indicates mass reserved for scientific instruments inside the pressure hull. Endurance figures given at a single horizontal velocity include the energy expenses of propulsion and communication of a 2 kbytes message on every cycle. Approximate costs are for a complete vehicle with conductivity, temperature and pressure sensors.

3.3 DESIGN CHALLENGES AND SOLUTIONS

The gliders described in Tables 3.1–3.4 are similar in overall characteristics because they were all designed to meet similar objectives. The ease of handling and low operating cost needed to make long time series feasible dictate small size and slow operating speed. Propulsion using buoyancy control follows Stommel’s Slocum vision and wide operational experience with autonomous floats and has some engineering advantages in eliminating shaft seals and moving external parts. Ultimately, however, evaluation of buoyancy propulsion will depend on energy efficiency and the value of sawtooth trajectories for sampling the ocean. We are aware of no modern efforts to design a long-duration, efficient, slow-speed AUV using a propellor and without this,

Table 3.1 Characteristics of Spray.

Hull	Length 200 cm, Diameter 20 cm, Mass 51 kg, Payload 3.5 kg
Lift surfaces	Wing span (chord) 120(10) cm, Vertical stabiliser length (chord) 49(7) cm
Batteries	Primary lithium sulfuryl chloride, 52 DD cells in 3 packs, Energy 13 MJ at 0 °C, Mass 12 kg
Volume change	Max 0.9 l, Motor and reciprocating pump, 50(20)% efficient @ 1,000(100) dbar
Communication	Orbcomm satellite, 2-way, 0.5 byte/s net, 400 J/kbyte, GPS navigation
Operating	Max P 1,500 dbar, U_{MAX} 0.45 m s^{-1}, Control on depth + altitude + attitude + vertical W
Endurance	$U = 0.25$ m s^{-1}, 18° glide, Buoyancy 0.15 kg, Range 7,000 km, Endurance 330 days
Cost	Construction $25,000, Refuelling $2,850

Table 3.2 Characteristics of Slocum Battery.

Hull	Length 150 cm (overall 215), Diameter 21 cm, Mass 52 kg, Payload 5 kg
Lift surfaces	Wing span (chord) 120(9) cm swept 45°, Stabiliser length (chord) 15(18) cm
Batteries	Alkaline, 260 C cells, Energy 8 MJ at 21 °C, Mass 18 kg
Volume change	Max 0.52 l, 90 W motor and single-stroke pump, Efficiency 50%
Communication	RF LAN, 5700 bytes/s, 3 J/Mbyte, 30 km range, GPS navigation
Operating	Max P 200 dbar, Max U 0.40 m s^{-1}, Control on depth + altitude + attitude + vertical W
Endurance	$U = 0.25$ m s^{-1}, 20° glide, Buoyancy 0.26 kg, Range 2,300 km (estimated)
Cost	Construction $50,000, Refuelling $800

Table 3.3 Characteristics of Seaglider.

Hull and shroud	Length 180 cm (overall 330), Diameter 30 cm, Mass 52 kg, Payload 4 kg
Lift surfaces	Wing span (av chord) 100(16) cm, Vertical stabiliser span (chord) 40(7) cm
Batteries	Primary lithium thionyl chloride, 81 D cells in 2 packs, Energy 10 MJ at 0 °C, Mass 9.4 kg
Volume change	Max 0.840 l, Motor and reciprocating pump, 40% (8%) efficient at 1,000(100) dbar
Communication	Cellular 450 byte/s net, 26 J/kbyte. Iridium 40 byte/s, 110 J/kbyte (predicted)
Operating	Max P 1,000 dbar, Max U 0.45 m s^{-1}, Control on depth + attitude + vertical W
Endurance	$U = 0.25$ m s^{-1}, 18° glide, Buoyancy 0.22 kg, Range 4,500 km, Endurance 220 days
Cost	Construction $60,000, Refuelling $1,375

Table 3.4 Characteristics Slocum Thermal.

Hull	Length 150 cm (210 overall), Diam 21 cm, Displacement 52 kg, Payload 2 kg
Lift surfaces	Wing span (chord) 120(9) cm swept 45°, Stabiliser length (chord) 15(13) cm
Batteries	Alkaline (for instrumentation, communication), Energy 6 MJ at 21 °C, 14 kg
Volume change	Max 0.4 l, 6 kJ harvested each cycle, 10 °C minimum temperature difference
Operating	Max P 1,200 dbar, Max U 0.27 m s^{-1}, Control on depth + attitude + vertical W
Endurance	$U = 0.25$ m s^{-1}, 38° glide, Buoyancy 0.235 kg, Range 30,000 km (estimated)
Cost	Construction $70,000, Refuelling $800

one cannot evaluate the conjecture that it is easier to make wings efficient. Even if propellor vehicles can be made equally efficient, the need to span large depth ranges to adequately sample the ocean would require buoyancy control systems or significant additional drag to generate the sawtooth trajectory that gliders come by naturally.

3.3.1 Buoyancy Generation

The innovative thermally powered Slocum is capable of a remarkable 30,000 km range. While this requires temperature differences sufficient to generate enough average power to overcome the drag inevitably associated with heat transfer and to deal with ocean currents, it is remarkable that a 50 kg AUV might circumnavigate the globe. While electric power may have a broader operating region, and the reliability of all the glider propulsion systems is yet to be proven, thermal power is too powerful a concept to be ignored in either gliders or profiling floats.

Two of the present gliders that use electric-motor powered buoyancy control systems have ranges at 0.25 m s^{-1} of more than 4,000 km. A single-stroke pump with a rolling diaphragm seal is used to pump seawater into and out of Slocum Battery. This approach is simple and has superior two-way buoyancy control, but it is difficult to accomplish in high-pressure applications. Seaglider and Spray use high-pressure reciprocating hydraulic pumps to transfer hydraulic fluid between internal and external bladders. While this allows a relatively small and light hydraulic system, controlled increases of buoyancy at high pressure require special metering and cavitation at the pump inlet can induce failure (Seaglider uses a separate boost pump to overcome this and Spray has an high-compression ratio pump to handle small bubbles). While optimization will depend on gaining more field experience, electric buoyancy control appears flexible and perhaps efficient enough for most missions.

3.3.2 Hulls and Hydrodynamic Performance

Drag and compressibility are largely determined by a glider's hull. For electric gliders these characteristics are important to achieving long duration and, consequently, low cost. Seaglider has the most sophisticated hull employing a fairing that encloses a pressure hull with compressibility matched to seawater. Ports in the fairing allow any trapped air to be vented before diving. A conventional low-compressibility hull of the size of the gliders described here loses O (0.1 kg) buoyancy as it descends from the surface to 1 km depth, increasing the pressure–volume work needed to ascend. Particularly when operating with small buoyancy, the associate energy loss is significant. On the other hand, conventional (and less expensive) hulls allow a larger payload, including a larger battery pack that provides the energy for this extra work.

Discussion of hydrodynamic performance is facilitated by Figure 3.8, which describes the behavior of Seaglider (Gliding dynamics and performance are discussed at length by Eriksen *et al.*, 2001 and Sherman *et al.*, 2001). Because of drag induced by lift generation, hydrodynamic performance (e.g. efficiency, speed) depends directly on speed and angle of attack and, indirectly, on glide angle. At fixed buoyancy forcing, horizontal speed is maximized at relatively steep glide angles for which angle

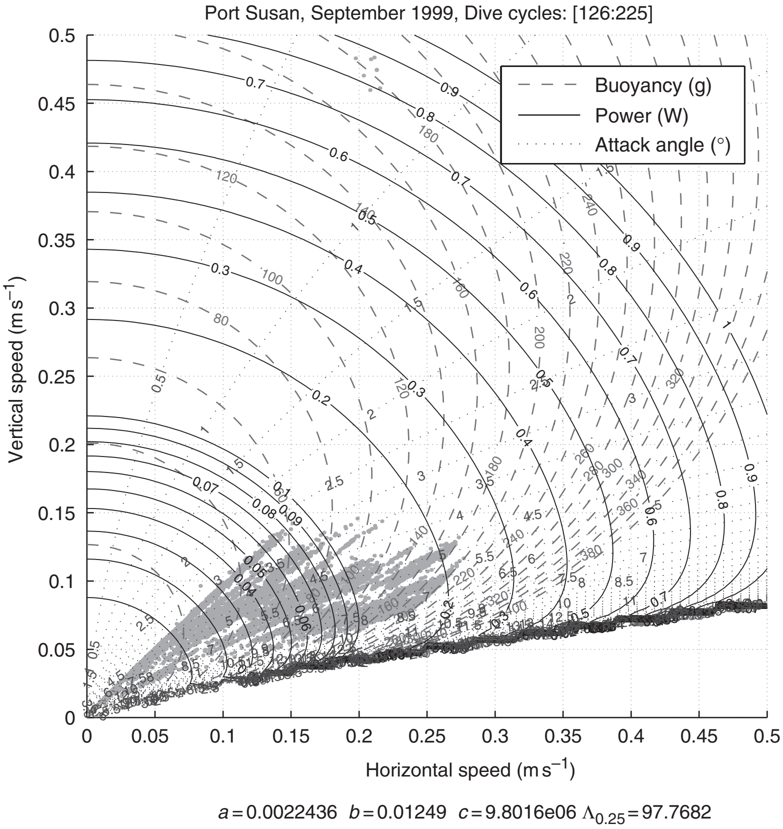

Figure 3.8 Glider performance diagram showing the buoyancy and power required to maintain a given speed and glide angle. This curve is for Seaglider but the behavior is similar for all designs. Note how at a given buoyancy, horizontal velocity U is maximized at a glide angle near 40°, whereas at fixed power U is maximized nearer a 14° glide. Green marks show observed Seaglider operating points. *See* Color Plate 4.

of attack and induced drag are minimized. At fixed power, however, speed peaks at a much shallower glide angle where induced drag is significant. All the gliders were designed with an objective of long range, which depends on the speed to power ratio, and, consequently, they use wings with high aspect ratios and high lift to induced-drag ratios.

It should be noted that the drag considerations differ somewhat between electric propulsion, where energy is limited, and thermal propulsion, where energy is unlimited but power is limited by the achievable heat transfer rate. An electric glider will typically operate near the shallow glide angle that maximizes range and at the minimum buoyant forcing to meet speed requirements. Heat flow and thermal power are, on the other hand, maximized by rapid cycling between depths with differing temperatures (overall speed affects the thermal resistance very little). For this reason, thermal gliders operate at relatively steep glide angles to increase vertical velocity. In these conditions low hull-drag is still highly desirable, but angle of attack and induced drag are low so that efficient, high-aspect-ratio wings are much less important than when energy is limiting.

Seaglider's uniquely shaped hull attempts to maximize the area over which the boundary layer in laminar. Spray has a conventional shape but efforts were made to find a low drag shape. Slocum, relying on the unlimited energy available with thermal power, uses a hull shape that simplifies construction and maximizes packing efficiency. Bio-fouling may increase vehicle drag significantly, as suggested by performance analysis on a one-month Seaglider mission in a fjord. In light of this and other uncertainties, the conditions under which each approach to hull design is to be preferred remains to be found through field experience.

3.3.3 Communication

Accurate navigation, the ability to transmit O(kilobyte) datasets quickly, and the ability to receive short messages adjusting operation are essential to autonomous operation. All the gliders described here use GPS navigation, which meets performance objectives admirably. Low-earth-orbit Orbcomm satellite (Spray), radio frequency Local Area Network communication (Slocum Battery) and Circuit Switched Cellular (Seaglider) communication have been used in the field, and System Argos is useful at least for emergency backup and locating. Low-earth-orbit systems have up to 5 orders greater speed and 3 orders better energy efficiency than Argos and additional systems (Iridium, Globalstar) are being implemented. These promise higher data rates and lower communication costs than are possible with Orbcomm. We are hopeful that at least one satellite system will survive the present economic competition.

Maintaining antennas clear of the surface in a seaway is the main technical challenge for communication and our gliders use different systems to achieve this. Seaglider and Slocums employ trailing antenna staffs that house the needed antennas. When on the surface these gliders pitch forward to raise these antenna staffs and Slocums employ an external bladder inflated by a small air pump to increase surface buoyancy and pitch moment. Spray's antennas are contained in a wing that is rolled vertical for navigation and communication. All systems are subject to loss of performance in high sea-states so adequate internal storage is necessary for several days of message buffering.

3.3.4 Gliding Control

Glider control involves monitoring performance, adjusting glide angle by controlling pitch and/or buoyancy, and adjusting heading by controlling roll or (for Slocum Battery) rudder position. All the gliders described here use Precision Navigation TCM2 attitude sensors to sense heading, pitch and roll and pressure sensors to measure depth and, from pressure rate, vertical velocity. Spray and Slocum measure altitude using an acoustic altimeter while Seaglider estimates altitude from measured glider depth and a digitally stored map of water depth.

A movable rudder gives Slocum Battery the tightest turning radius (approximately 7 m) and allows turning without significant roll so that the acoustic altimeter, critical in shallow-water operations, remains accurate. The other gliders, intended for deep water, typically roll about 30° to achieve turning radii of 20–30 m. Because glide angle and performance are sensitively linked, gliding is generally more closely controlled than turning. In normal gliding Spray adjusts pitch around a set point using proportional control on O (60 s) intervals while infrequently adjusting buoyancy to maintain vertical velocity within an operating range. Seaglider operates similarly, controlling gliding on a longer interval of O (300 s) and uses buoyancy adjustment as a primary control. Both vehicles accelerate control at the minimum and maximum depths where buoyancy and pitch are changed significantly. Seaglider is unique in using an onboard Kalman filter to estimate currents and adjust target heading and glide angle to compensate for them.

3.3.5 Sensors

Scientific payloads for gliders are limited by size, flow disturbance, and power requirement considerations. Sensor systems must fit within the payload fraction of O (50)-l vehicle and, because gliding involves modest buoyancy forces ($\sim$0.2–4 N), ballast and trim are paramount considerations. Sensors must be hydrodynamically inobtrusive, lest they spoil gliding performance by adding drag. For example, wind tunnel tests of Seaglider demonstrated that appending a toroidal conductivity sensor with 2% of the vehicle's frontal area added more than 25% to its drag. Streamlining can be achieved by using sensors that are small or mounted flush to the vehicle hull. Outward-looking acoustic and optical sensors conveniently fit this requirement and have been used on the gliders described here.

The overall power consumption of the four gliders discussed here is O (1 W). Achieving this requires low-power electronics and sampling schemes that limit the duty cycle of sensors. Slow glider speeds allow sampling intervals of O (10 s) to achieve vertical resolution of O (1 m) but sensors with limited energy usage are still important to the overall power budget. For example, sampling temperature and salinity consumes roughly 0.1 J, dissolved oxygen about 0.4 J, and fluorescence and optical backscatter about 2 J. Glider controllers use O (0.1 W) when not in low-power sleep mode and particularly for low throughput systems, data transmission is also a significant factor in the power budget.

Like autonomous floats, gliders achieve their economy by having moderate construction costs and long operational lifetimes. Achieving this economy therefore requires scientific sensors that are stable over many months. The primary challenge to stability is bio-fouling. Compared with floats using Argos communication, gliders can reduce fouling by spending little time on the surface and in the euphotic zone. Avoidance of exposure to the sea surface itself also avoids surfactants which affect conductivity sensors, so keeping instrumentation submerged while gliders communicate is presumably helpful. Stability of temperature, conductivity (Bacon *et al.*, 2001; Riser and Swift, 2002) and optical sensors over many months has been achieved by profiling floats (Davis *et al.*, 2001), and a glider's exposure to the euphotic zone is only slightly worse.

3.3.6 Operating Costs

The principal operating costs of gliders are vehicle preparation (including energy cost), deployment and recovery, and communication. The small size and long range of the gliders described here implies low logistic overhead for operations compared to reliance on research vessels. Nearshore launch and recovery from small boats in daylight and fair weather by a crew of one or two is sufficient for glider access to most of the ice-free ocean. Communications costs depend strongly on method. Costs for global coverage range from O ($10/kbyte) for Orbcomm to O ($0.30/kbyte) for Iridium. Battery costs are of the O ($1) per deep-ocean vertical cycle. Thus even with construction costs amortized over a few deployments, the operating costs for a mission reporting hundreds of multivariable samples in each of a thousand dive cycles is about $10,000, about the same as one day of research-ship time. In perspective, gliders can collect several multivariable (e.g. temperature, salinity, velocity, oxygen, fluorescence, optical backscatter, etc.) profiles for the cost of a single expendable bathythermograph (XBT) probe.

3.4 EXAMPLES OF OBSERVATIONS

Glider technology is new and its capabilities have yet to be fully demonstrated in field experience. Nevertheless, the three battery-powered vehicles have all produced datasets that begin to sketch out how gliders can be used. They have been successfully used with, in various combinations, temperature, conductivity, dissolved oxygen, fluorescence and optical backscatter sensors. They have been used in single- and multi-vehicle arrays to collect time series of up to one-month length, time series of short sections, and a 270 km section over 13 days. This section describes some of that data.

All the gliders have also been used to measure vertically averaged currents from the difference between dead reckoning and GPS navigation. Dead reckoning is based measured headings and speed through the water based on measured vertical velocity, pitch and buoyancy. A model is used to infer angle of attack from buoyancy and pitch (assuming ocean vertical velocity is negligible). With measured pitch, the angle of gliding is calculated and from this vertical velocity determines horizontal speed through the water. Considering the main errors (vertical ocean velocities and errors in the angle of attack), depth-average current measurements are accurate to O ($1\,\mathrm{cm\,s^{-1}}$) over O (1 h) time intervals. When data from many depth cycles are combined, the measurement of depth-average velocity becomes quite accurate, and when coupled with sections of ocean density, allows gliders to accurately estimate absolute geostrophic currents. Thus gliders can attack the long-standing problem of hydrography: properly referencing geostrophic shear. The velocity estimates also provide accurate measurements of gliding performance. The performance figures for Spray and Seaglider given in Section 2 are based on these analyses; performance for Slocum is predicted.

3.4.1 Time Series (Virtual Moorings)

During a July 2000 field trial at the Rutgers LEO-15 research site near Tuckerton, New Jersey, a Slocum Battery completed a 10-day deployment in which it collected a 5000-dive time series of temperature, salinity and vertically averaged velocity. On average every 150 s the Slocum dived to 15 m depth, triggered on depth and altitude above the shallow bottom. Data was relayed to shore using an RF-LAN and on occasion control of the vehicle was switched between Tuckerton and Falmouth, Massachusetts using an Internet to LAN connection. The Slocum mainly maintained station but, on command, also completed one 15 km cross-shelf section.

The field trial included Acoustic Doppler Current Profilers and CODAR HF radar to remotely sample near-surface currents that provide comparisons for the depth-averaged currents measured from the Slocum. Figure 3.9 shows time series of the Slocum velocity, the vertical average of an ADCP sampled when the Slocum was within

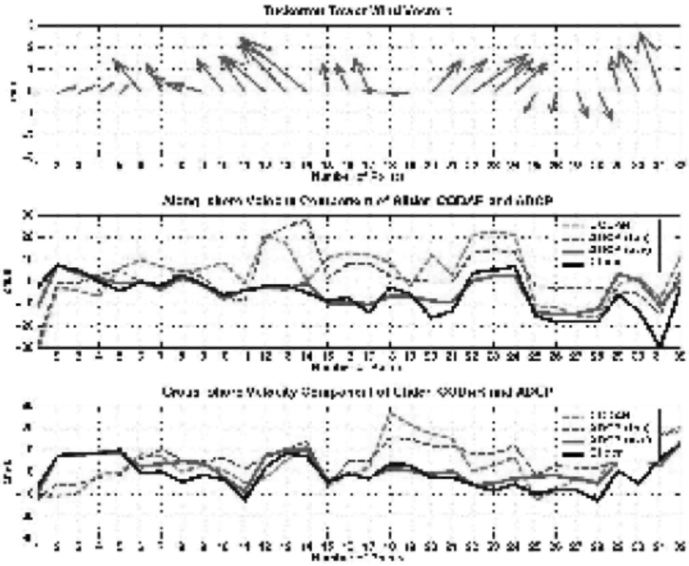

Figure 3.9 Time series of wind, depth-average ocean velocity from Slocum (black), depth-average ADCP velocity (red), and near-surface velocities from CODAR (dashed green) and ADCP (dashed black) from the LEO-15 site during July 2000. *See* Color Plate 5.

2 km, as well as surface velocities inferred from CODAR and the ADCP's 3-m depth bin. There is substantial vertical variability but the Slocum and vertically averaged ADCP compare well with an rms difference similar to that between ADCP measurements at 3 and 6 m at the same site or between sites separated across-shelf by 4 km. Some of the ADCP-Slocum difference likely also results from lateral variability. One can imagine more complex depth vs. time patterns that would allow measurement of the vertically averaged flow in vertically stacked depth ranges.

Seaglider and Spray participated in Office of Naval Research supported multi-vehicle sea trials in Monterey Bay during the summers of 1999 and 2000. In 1999 the Spray prototype was virtually moored in 450 m depth in Monterey Canyon for 10 days (see Sherman *et al.*, 2001). An acoustic altimeter established the bottom of profiles within a few meters of the bottom. The temperature and salinity time series showed internal wave motion to be bottom intensified in the canyon. In the face of internal-wave motions of O (15 cm s^{-1}) and a mean current measured to be about 3 cm s^{-1} up-canyon and to the south, surface position was maintained with standard deviation near 500 m.

Starting in June 2000, a Seaglider was virtually moored for a month in Possession Sound, a 3 km wide fjord in western Washington. In April 2001, two Seagliders were virtually moored at 1.5 km separation for a week across the Sound. Comparison of velocity computed from geostrophic shear and measured depth-averaged flow compared well with surface currents, showing that the exchange flow is largely geostrophic (Chiodi and Eriksen, 2002). These operations show how accurately positioned virtual moorings can be easily established.

3.4.2 A 270-km Section

In October 2001 a Spray was sent to sample temperature, salinity and optical backscatter along a 270 km across-shelf section southwest of San Diego. The glider was deployed not far from shore from a small boat. It dove to 500 m (or the bottom if detected by an acoustic altimeter) with buoyancy and glide angle to produce forward velocity near 0.25 m s^{-1}. The course was initially west from San Diego and then southwest, crossing one shallow bank. Data and mission-control commands were relayed by Orbcomm satellite, mainly in the mode used for global communication. The section was completed in 13 days. The vertically averaged velocity (generally averaged over 500 meters) is shown in Figure 3.10 and the section of density is portrayed in Figure 3.11.

Figures 3.10 and 3.11 show how gliders could dramatically improve monitoring of the coastal environment. Figure 3.11 shows the slope of isopycnals that, through geostrophy, define vertical variation of flow through the section. The isopycnal's broad downward slope to the east demarcates the shear of the California Current – compared with deep water, surface flow is to the south toward the equator. The isopycnal upturn near the coast indicates a reverse shear that is usually indicates a shallow nearshore poleward countercurrent but might also indicate equatorward flow at depth. Cost prevents the quarterly CalCOFI shipborne survey from resolving this feature, but the glider survey's close "station" spacing makes its details quite clear. Spray's absolute transport measurements show a weak ($\sim$1 cm s^{-1}) average southward flow in the upper

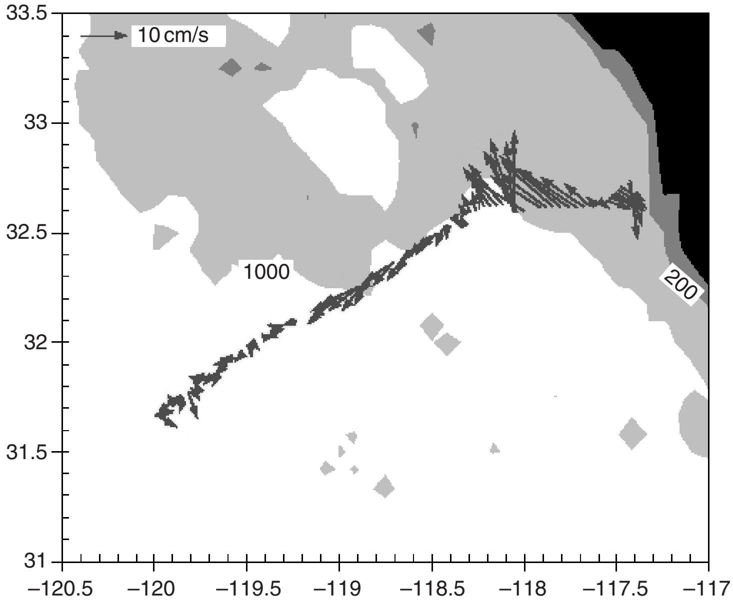

Figure 3.10 Absolute velocity averaged over the upper 500 m from a 150 nm Spray section off San Diego CA. The section was carried out to the southwest in 13 days. The 200 m and 1,000 m isobaths and the coast are shown.

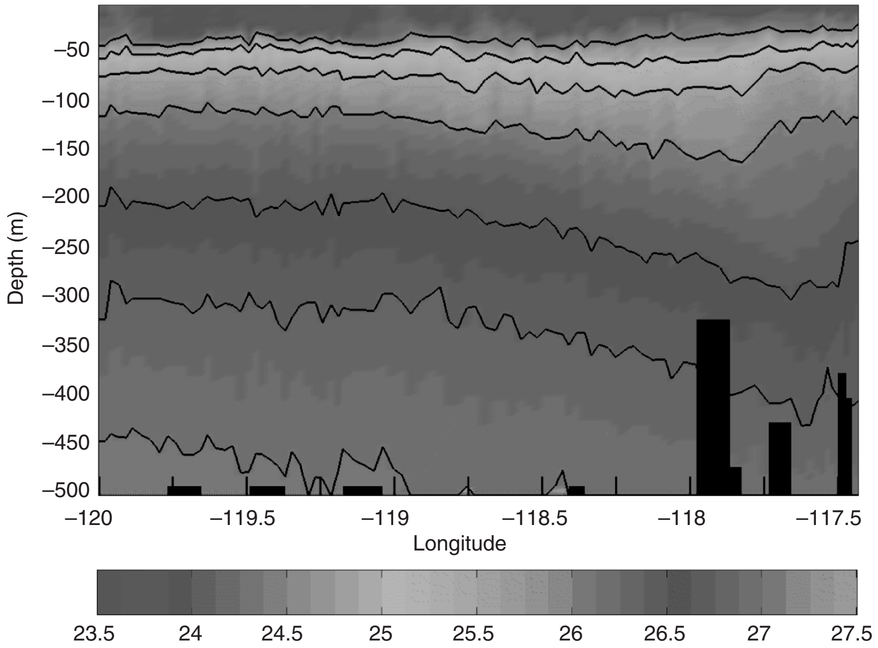

Figure 3.11 Density from the Spray section in Figure 3.10. Spacing of the temperature and conductivity profiles is about 3 km. The broad isopycnal slope downward to the east indicates the geotrophic shear of the California Current. The nearshore upward slope is associated with a near shore countercurrent. *See* Color Plate 6.

500 m west of 118.5°W as expected from the California Current. The structure of the poleward flow, concentrated some 50 km off the coast, however, could not be anticipated from geostrophic shear and this emphasizes the importance of glider velocity measurements. Highly resolved hydrographic surveys with velocity references and the ability to identify barotropic and/or ageostrophic flows make gliders a powerful way to observe the coastal ocean. For example, a pair of gliders could, at quite feasible cost, produce a time series of sections like those in Figures 3.10 and 3.11 with an average sampling interval of one week.

3.4.3 Repeated Multi-vehicle Sections

Three Seagliders were used in August 2000 Monterey Bay trials to demonstrate an ability to gather repeated surveys using mulitple coordinated vehicless, something that remains a rare luxury using ships (Figure 3.12). All data, as well as commands to the vehicles, were telemetered via cellular telephone in near real time to and from computers ashore and aboard a small vessel. The first sampling task was to

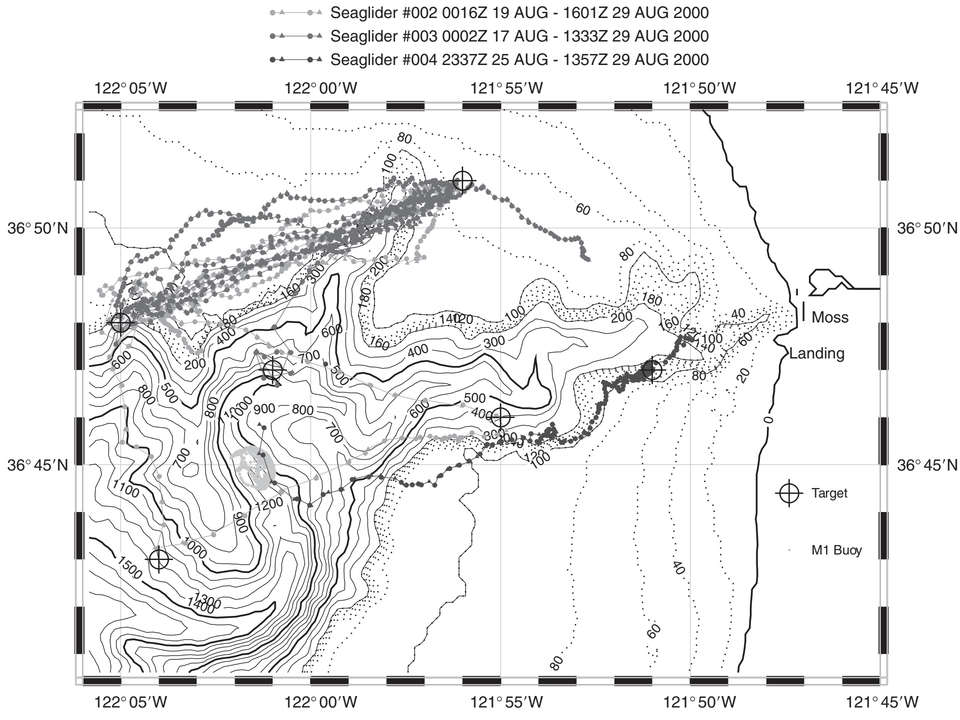

Figure 3.12 Tracks of three Seagliders in Monterey Bay (depth contours in meters). Two gliders made a total of 13 sections along the north rim of Monterey Canyon. At the end of the exercise, one of these (track in red) remained near a target about 2 miles north of a surface mooring (buoy positions shown in cyan). *See* Color Plate 7.

repeatedly collect sections across the continental shelf at the entrance to the bay. Two gliders simultaneously surveyed a 15 km long transect on the northern edge of a large submarine canyon for 10 days. Temperature and salinity sections collected described the development and decay of a wind-forced surface mixed layer. The vehicles dove to within a few meters of the bottom or 250 m, whichever was shallower, demonstrating the ability to navigate over topography using a bathymetric map.

At the end of the exercise, one Seaglider was commanded to a target about 3.5 km north of the anchor position of a surface mooring maintained by the Monterey Bay Aquarium Research Institute. A tight cluster of surface positions (red symbols, Figure 3.12) demonstrated that this virtually moored glider held position at least as well as the moored surface buoy (cyan symbols, Figure 3.12). The excercise also demonstrated how a glider can, under remotely relayed commands, operate in different modes on the same mission.

3.5 THE FUTURE

Glider operations are in their infancy and the next step is clearly to use the developed technology to address scientific and environmental problems in order to develop procedures to interpret glider data, to refine and make more reliable the technology, and to assess the importance and adequacy of different technical characteristics (e.g. cost, energy efficiency, speed, endurance, reliability, and communication rate). There are many problems not yet solved. For example, how often do sharks attack these swimming aluminum fish? Can low drag be maintained for months in the presence of biofouling? Which sensors are adequately stable? These questions can only be answered from field experience. Gathering this experience can and should also advance ocean research. One would expect new technical approaches, such as those described in Chapter 15 and new combinations of existing approaches to appear in new gliders as a result of the experience gained over the next few years.

Gliders should play an important role in the emerging global ocean observing system, supplementing data from the Argo array of profiling floats particularly in regions of high interest where the Argo array has too little spatial resolution or where it is important to separate time and space variability more completely. Boundary currents, the equator, high-latitude convection regions, and continental shelves are regions where gliders in virtually moored or repeated-survey mode are likely to be valuable. Gliders will also serve as handy and efficient platforms for gathering long environmental records of variables not widely measured by operational systems. Their low cost and operational flexibility will likely also make them useful in short-term intensive campaigns. For this, new methods of communication (including underwater links) and more extensive schemes for control of networked gliders need to be developed.

The utility of all autonomous observations depends on availability of suitable sensors for a wide range of physical, optical, chemical, and biological properties. For gliders, which achieve economy through long life and low hydrodynamic drag, stability, low power and small size are key attributes. Biofouling is the primary concern for stability. It can be predicted that early successes with available sensors on gliders will provide impetus to expand the suite of variables that can be measured.

In looking back on Stommel's 1989 article anticipating autonomous gliders, we marvel at how much of what followed he had predicted. While lacking his vision, we are confident that this approach to ocean observation is just now reaching the limit of what he foresaw and that new innovation will soon carry us to areas we cannot see now.

Annotations from Chap03.pdf

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