

# Autonomous Underwater Gliders

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## ***Background***

The motivation for developing autonomous underwater gliders is essentially economy. Oceanographers would know more about the ocean if the access price were lower. Ships have served the ocean community well in describing the basic phenomenology of physical, chemical, biological, and geological processes at work in the oceans. Yet these processes invariably occur at temporal and spatial scales too short to be resolved, and extents too long to be covered, by ship-based measurements without prohibitive cost.

The need for technology to collect oceanic sections by remote control without the cost of ships was recognized by Henry Stommel in the early days of WOCE, the World Ocean Circulation Experiment. In a science fiction article written with the perspective of an oceanographer reminiscing in 2021, he wrote, “A really new method was needed, one that would provide subsurface data on a scale and at a frequency that matched what remote sensing by satellite provided for the sea surface. Multiplying the number of ships by a factor of 100 was economically out of the question.” (Stommel, 1989). The article went on to describe a network of 480 remotely controlled long range autonomous underwater gliders making repeat sections, “on a monthly basis, all the 48 hydrographic sections that took the (WOCE Hydrographic Program) 12 years to do once.” The technical specifications for the gliders he described are more or less those of the class of platforms that has been under development over the last several years.

Doug Webb had the idea for a thermally powered glider and approached Stommel with it in 1988. Stommel suggested naming it after Joshua Slocum, the New Englander who made the first single-handed global circumnavigation in his small sailboat *Spray*. They secured a contract from the Office of Naval Technology in 1990 to develop a battery powered prototype with which they made 29 dives to as much as 20 m depth in Wakulla Springs FL in January 1991 and 14 more dives in Seneca Lake NY in November that year. Stommel passed away two months later. The basic features of their prototype survive in the current generation of gliders: buoyancy engines coupled with mass shifters to control vehicle attitude. The idea is simple enough that an enterprising engineering student recently built a glider from LEGO parts for her senior thesis at Princeton (it fits in her briefcase). Making the transition to a functioning open-ocean glider has been the challenge over the last decade.

The Office of Naval Research awarded about 30% of its support for an Autonomous Oceanographic Sampling Network (AOSN) program to develop seaworthy gliders from 1995 to 2000. Three glider development groups emerged from the AOSN program, which featured demonstration experiments showing that gliders could navigate at sea under remote control and return

data in near real-time. Webb Research Corporation developed Slocum, a Scripps Institution of Oceanography / Woods Hole Oceanographic Institution consortium developed Spray, and a University of Washington group developed Seaglider. Details of these gliders are available from Webb *et al*, 2001, Sherman *et al*, 2001, and Eriksen *et al*, 2001. A summary of all three groups' progress is in Davis *et al*, 2002.

The design philosophy of gliders follows that for profiling floats: a distributed network of modestly priced platforms is appropriate to studying systems where no single element is vastly more important than any other so that integration over the system is requisite. The fluid ocean is such a system and a distributed approach provides the fault tolerance to understand it. The safety of numbers means that loss of a few platforms is not devastating to the network. This approach is the opposite of that taken by cabled observatories, for example, focused on systems where all the interesting signals are highly localized in space and time (e.g. volcanic eruptions). It also is counter to the temptation to overly complicate platforms so each becomes invaluable, a common tendency in oceanographic instrumentation.

### ***Glider Fundamentals***

Underwater gliders are buoyancy-driven devices; they alternately reduce and expand displaced volume to dive and climb through the ocean, just as do profiling floats. Unlike floats, gliders additionally carry wings and control their pitch attitude to effectuate a horizontal speed component through the ocean. They turn by rolling their wings or by use of a rudder. Buoyancy control, coupled with hydrodynamic lift is a natural choice for a platform designed to both profile and traverse the stratified ocean where gradients are near vertical and the tilt of surfaces is of key importance. Sensible sampling dictates glide slopes steep compared to isopleths, hence ocean gliders need not attain the shallow slopes of sail planes in the atmosphere.

Gliders must have both long range and high endurance to be independent of and an effective alternative to ships. Energy considerations are paramount. Although propulsion energy is spent only on ascent (dives are free), ultimately the pressure work done is dissipated against hydrodynamic drag. Since drag is roughly quadratic, halving speed quadruples endurance and doubles range through the water. It is useful to reduce speed only to the point that further reduction impairs the ability to navigate against currents. While typical propeller-driven autonomous underwater vehicles zoom around at a few meters per second for a few hours to cover a few tens of kilometers, gliders are designed to slip through the ocean a fraction of a meter per second for months to cover several thousands of kilometers. Existing gliders run at about half a knot on half a watt.

Glider economy stems from long range, small size, remote control, and modestly priced data communication. These attributes allow gliders to rove the open ocean without reliance on ships, being launched by hand from a small boat and recovered much later for reuse. A mission is controlled from any computer with communication access. The operational cost of making a section, including launch, recovery, refurbishment, and telemetry is as low as \$2 per km. Individual multi variable profiles to 1 km depth with 2 m resolution cost a few dollars each. Gliders can be operated for a year for the cost of a single day of research vessel operation. Fabrication cost is equivalent to the cost of 2-4 days of ship time.

Instrumentation must be small, low-power, and hydrodynamically unobtrusive to function effectively on a glider. On a 50 kg vehicle, in practice typical instrumentation is limited to perhaps 1 kg, exclusive of batteries, controller, and pressure case. Typical sensor package energy consumptions of  $O(0.1J)$  per sample allow sustained  $O(1m)$  depth resolution (examples are temperature, conductivity, and dissolved oxygen by a membrane flux method). Sensors with higher consumption ( $O(1J)$  per sample) demand coarser depth resolution or less coverage (examples are active optical sensors using LEDs to measure fluorescence, optical backscatter, or dissolved oxygen optically and active acoustic sensors to measure current). Sensors which disturb flow can account for a large fraction of the overall vehicle drag, despite comprising but a tiny fraction of vehicle volume. Sensitivity to moments requires that sensor packages be arranged so as not to interfere with the range of pitch and roll necessary for effective glide control. Because of these constraints, gliders are more highly integrated systems than most oceanographic instruments.

Range and endurance are highly dependent on mission objectives and the operating environment. In battery powered gliders, perhaps 80% of available energy is devoted to propulsion, with the rest applied to control, sensors, communication, and navigation. The high pressure pumps used to change buoyancy are inefficient at low pressure, so that deeper dives result in much longer range. Deeper dives also tend to encounter less current on average, leading to increased range over the ground. Finally, deeper dives imply a lower duty cycle drifting at the sea surface while communicating and navigating. These three factors make deep diving open ocean range and endurance dramatically longer than for shallow dive missions. Factors favoring shallow dive missions can be a need to sample more often in time, focus on upper pycnocline processes, or shallow water depth. The cost of a mission is nearly independent of its length, so the expense rate of using gliders is roughly inversely proportional to dive depth, range, and mission duration. The costs of deployment and recovery, and refurbishment together roughly equal data communications costs.

Ocean-going gliders are entirely autonomous, yet their operation can be controlled via two-way telemetry. Given a set of mission parameters, gliders follow them until they are changed, reporting data as often as they surface. They dead reckon while submerged, and the difference between displacement through the water and over ground on each dive cycle provides an estimate of depth-averaged current. The difference between GPS fixes taken while drifting at the sea surface during a communication session gives an estimate of surface current, although gliders are not ideal drogues. Glider control can even adjust heading to take account of inferred current calculated underway to optimize progress toward a programmed target. Homing on a single target while close to it results in a ‘virtual mooring’ mode of sampling, where a glider maintains geographic position at least as well as instruments moored to an anchor. Homing on a sequence of waypoints produces a section survey mode. Gliders can operate in either mode during the same mission through remote control.

Glider estimation of depth-averaged current provides a reference for geostrophic shear inferred from lateral density variations, solving a problem that has plagued hydrographers for more than a century. Profiling floats similarly rely on drift at a common depth. Using depth-averaged flow as a reference works over topography where a deep common depth is unavailable, so that gliders can estimate absolute geostrophic currents close to the ocean margins as well.

Near real-time data return allows the possibility of adjusting sampling during the course of a mission to react to environmental conditions. Telemetry rates via low earth orbit satellites are sufficiently inexpensive in both energy (~30 J/kilobyte) and cost (~\$0.20/kilobyte) that the data return from a single glider (~120 kilobytes/day) is nearly that originally envisioned for the entire 3000-float Argo fleet using ARGOS while being a factor of ~200 less expensive. Reaction to observed signals with new control commands is typically delayed by one dive cycle.

Power is provided by batteries for all of the existing glider models, but for one, Thermal Slocum, power for propulsion is harvested from the thermocline. This feature promises the possibility of several fold range and endurance extensions, since batteries can be devoted to electronics and trim functions. The buoyancy engine in this model employs a wax that melts at subtropical mixed layer temperatures to compress a gas which is used to expand vehicle volume at the bottom of a dive. Battery propelled gliders are necessary for subpolar regions or where buoyancy is controlled by salinity.

### ***Field Experience***

Gliders are still some way from attaining their range and endurance design specifications. Stommel's fantasy had a Slocum crossing the Atlantic by 1995 and the New York Yacht Club funding a glider circumnavigation race with Australian and French rivals by 1996. He had the French winning. (He could hardly have predicted that yachting's America's Cup would be held by the Swiss in 2003.) In real life, gliders had barely been immersed in seawater by 1997. By 1999, Spray and Seaglider had completed 10 day missions, with Slocum doing the same a year later. In 2000, three Seagliders executed a sequence of cross-shelf sections in Monterey Bay and in 2001, a Spray made a 280 km section southwest from San Diego. A Seaglider travelled over 1000 km through the water making repeat sections off the Washington coast in 2002 and another endured winter storms for a month on the continental shelf near Seward AK. Early in 2003, a pair of Electric Slocums were used on the Florida shelf in a sequence of vessel-tended operations, the first operation of gliders by other than their developers. A Thermal Slocum underwent trials in the Tongue of the Ocean last month.

Gliders appear near the end of their development phase for the current generation of battery powered models. While they have yet to finish missions close to the limits imposed by battery capacity, they are presumably not far from doing so. The current environmentally powered model has only recently begun its field testing phase. Considerable experience will be required to increase reliability.

### ***Challenges Ahead***

The outstanding questions for gliders are what problems will emerge from a few years of field use. A couple of the open ocean missions to date have ended with juvenile barnacles attached, with attendant increase in hydrodynamic drag evident in at least one. Issues of corrosion or other potential fouling issues have yet to be discovered. Since gliders are reusable, questions of wear arise. The necessary levels of maintenance have yet to be established for glider components.

The availability of low-power satellite data communications is crucial, yet all commercial providers of such service used by gliders to date have gone through bankruptcy, begging the question of stability. In 1995, prospects for low power satellite telecommunications looked very promising. Today it appears but a niche market, surviving largely due to military demand.

Transfer of glider technology is in its infancy. Webb Research has sold Electric Slocum gliders to four customers. The Seaglider and Spray user groups have expanded by entraining investigators from within their respective institutions. Demand for gliders is persistent, both domestically and internationally. How to best meet that demand is an unanswered question. Presumably, operation by a broad number of users will result in wide application of glider technology to oceanographic problems. Ideally, an investigator and a technician can operate a few gliders backed by producers who provide services inaccessible to small groups.

If the development experience of profiling floats can be used as a guide, by the end of the present decade, glider technology will have made a clear scientific mark on the seascape. In the intervening years, gliders will mature as developers and groups of users exercise its capability.

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