Special Issue—Ocean Observations

Observing the Ocean with Autonomous and Lagrangian Platforms and Sensors (ALPS): the Role of ALPS in Sustained Ocean Observing Systems

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The chief source of ideas in oceanography comes, I think, from new observations.
—Henry Stommel, 1989

Oceanographers have long dreamed of a detailed, 4-D view of the ocean. The last decade has witnessed a revolution in autonomous ocean observing capabilities as new platforms and sensors developed, and rapidly matured. As these systems become fully operational, and integrated with other components of the ocean observing system, oceanographers will move closer to realizing this dream. The new generation of oceanographic platforms has been characterized as "autonomous" because the platforms operate—tracking water masses, recording oceanographic properties, and transmitting data home via satellite telemetry—without a tether to either the seafloor or a ship. Autonomous platforms are diverse in their mechanisms and rates of motion; mission payloads, ranges and durations; and capabilities to change sampling parameters during a mission either by receiving commands from home or by using on-board, decision-making tools. The platforms encompass Lagrangian surface drifters, neutrally buoyant and profiling floats, highly controllable self-propelled AUVs (Autonomous Underwater Vehicles), and underwater gliders that adjust their buoyancy to glide forward through the ocean in a saw-tooth pattern. Each platform genre has its own optimum sampling domain, capability to incorporate sensors, and unique potential to contribute to sustained observation of the ocean, such as the U.S. Integrated Ocean Observing System (IOOS).

Parallel to the evolution of autonomous platforms has been the revolution in new sensing systems for biological, chemical, and optical properties. The new sensors are small but robust, stingy power consumers that sample fast enough to resolve bio-geo-chemical parameters on the same space and time scales as physical properties. Wireless communication allows all of these data to arrive at oceanographers' desktops, and be posted on the Web, within hours of collection. The combination of *autonomous and Lagrangian platforms and sensors* (i.e., ALPS; Table 1) has ushered in a new era of sampling that is truly interdisciplinary in character and shows great promise for contributing to major advances in our understanding of ocean processes.

Because of the new and rapidly evolving nature of this sampling mode, no concerted plan existed that detailed the new opportunities enabled by ALPS or provided a blueprint for enabling them. In Spring 2003 the ALPS Workshop brought 50 participants together in La Jolla, California, to develop a national plan to enable broader community participation in the ALPS activities. Issues addressed included scientific questions that could be uniquely addressed by ALPS alone and in conjunction with other sampling modes such as ships and cabled observatories, specifically the OOS; technological developments needed to develop even more capable sensors and platforms; mechanisms for enabling broader community access; and needs for training and education. A full workshop report is available at http://www.geo-prose.com/ALPS/.

In this article we summarize the four genres of platforms and give examples of recent scientific accomplishments using autonomous platform/sensor systems. Next, we discuss the potential for ALPS to contribute to sustained ocean observation and experimentation. Lastly, we summarize the workshop's recommendations for the future.

Near-Surface Drifters

Lagrangian surface drifters are perhaps the oldest technique for ocean velocity measurement. Scientific publication dates back two centuries when Benjamin Franklin (1785) published his observations of ocean currents using buoys and drogues. In the last century and a half, the typical drifter has consisted of a floatation device tethered to a drogue set at a predetermined depth (Figure 1a). Sequential location observations of

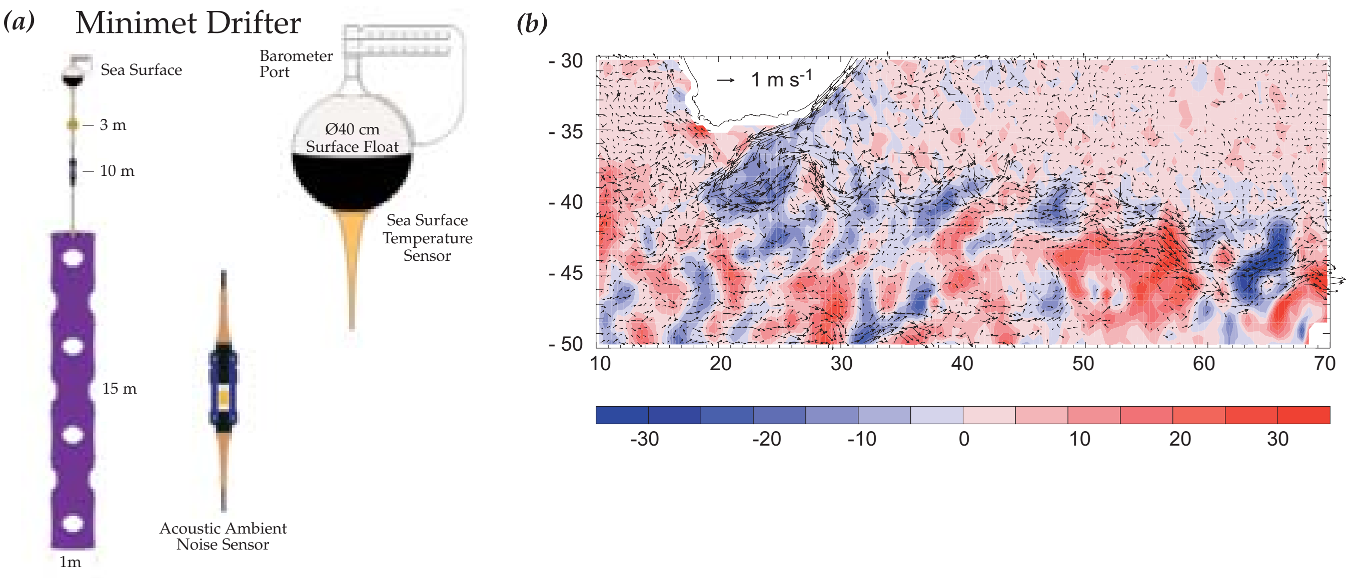

Figure 1. a) *Schematic of Minimet drifter that measures wind speed with "Wind Observations Through Ambient Noise" (WOTAN) and wind direction by computing the most likely direction from a large number of samples. Most recent air-deployments of Minimets were in September 2003 in front of Fabian, a class 4 hurricane;* ***b)*** *The 1978-2002 time-average drifter observed velocity on 0.5º resolution in the Aghulas Extension (color bar) is overlain with QuikSCAT wind divergence computed from 0.25º resolved observations, 2000-2003. Semi-permanent meanders occur; wind convergence is located at each of seven semi-permanent northward deflections of the surface current. These unique data imply that the ocean mesoscale forces atmospheric variability in mid-latitudes. (Peter Niiler, Scripps Institution of Oceanography, by permission.)*

Table 1.
Platforms and their characteristics

Platform	Mode of operation	Typical deployment duration	Spatial scales	Sensor payload
Surface drifter	Floats on surface, sometimes drogued at depth	Weeks to years	Regional to global	Moderate, power-limited
Float	Neutrally buoyant, sometimes profiling	Weeks to years	Regional to global	Moderate, power-limited
Glider	Profiles, controls horizontal position by gliding	Weeks to months	Regional	Light, power and size-limited
Autonomous Underwater Vehicle	Powered with propeller	Hours to days	Small	Heavy

the drifter's position are used to compute an ocean current or 'drift'. With the advent of satellite communication in the early 1970s, came a rapid increase in the use of drifters that transmitted position and data from *in situ* sensors via satellite. Considerable research was invested to develop drifter systems with longevity on the scale of years; to determine optimal float, tether and drogue characteristics to ensure accurate water-following characteristics; to enable ease of deployment from a variety of vessels even under challenging weather conditions; and to provide both drifters and data transmission at reasonable cost. Surface drifters have been used in both the open ocean and coastal waters, providing a persistent presence in the surface ocean (Figure 1b).

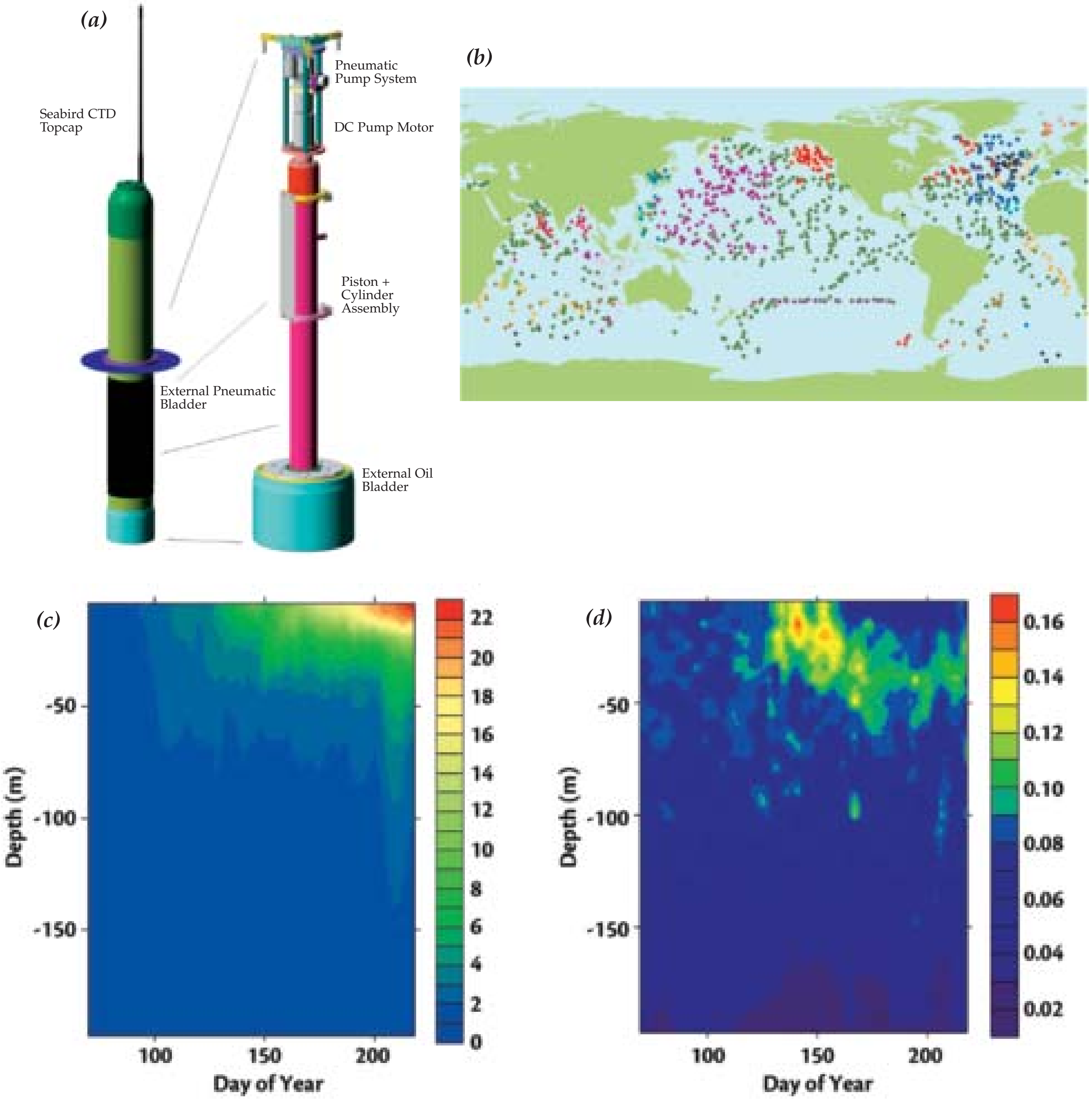

Figure 2. a) *Profiling floats like the SOLO float (Sounding Oceanographic Lagrangian Observer) are the workhorses of Argo, an international activity whose mission is to monitor measure mid-ocean circulation and the temperature and salinity structure of the upper 2000 m. The floats drift at depth (typically 1000m), surfacing approximately every 10 days over their 5-year lifetime. A total of 3,000 autonomously profiling floats are envisioned in a global array to provide continuous observations for climate monitoring and prediction, with all data publicly available within hours of transmission (Russ Davis, Scripps Institution of Oceanography, by permission);* ***b)*** *An example of Argo's global coverage can be seen in the location of floats, deployed by 18 countries, as of November 203. The Argo Network float deployment began in 2000; as of November 2003, 951 floats are operational (ftp.jcommops.org/Argo/Maps);* ***c and d)*** *A SOLO float with temperature (c) and optical (d) sensors was deployed in the Sea of Japan in Spring 2000 to observe the development of a phytoplankton bloom (recorded as an increase in 490-nm light attenuation coefficient) following thermal stratification. After nutrients in surface waters were depleted, a subsurface phytoplankton layer was established. This mission demonstrates the power of integrating bio-geo-chemical sensors into profiling floats (Greg Mitchell, Scripps Institution of Oceanography, by permission).*

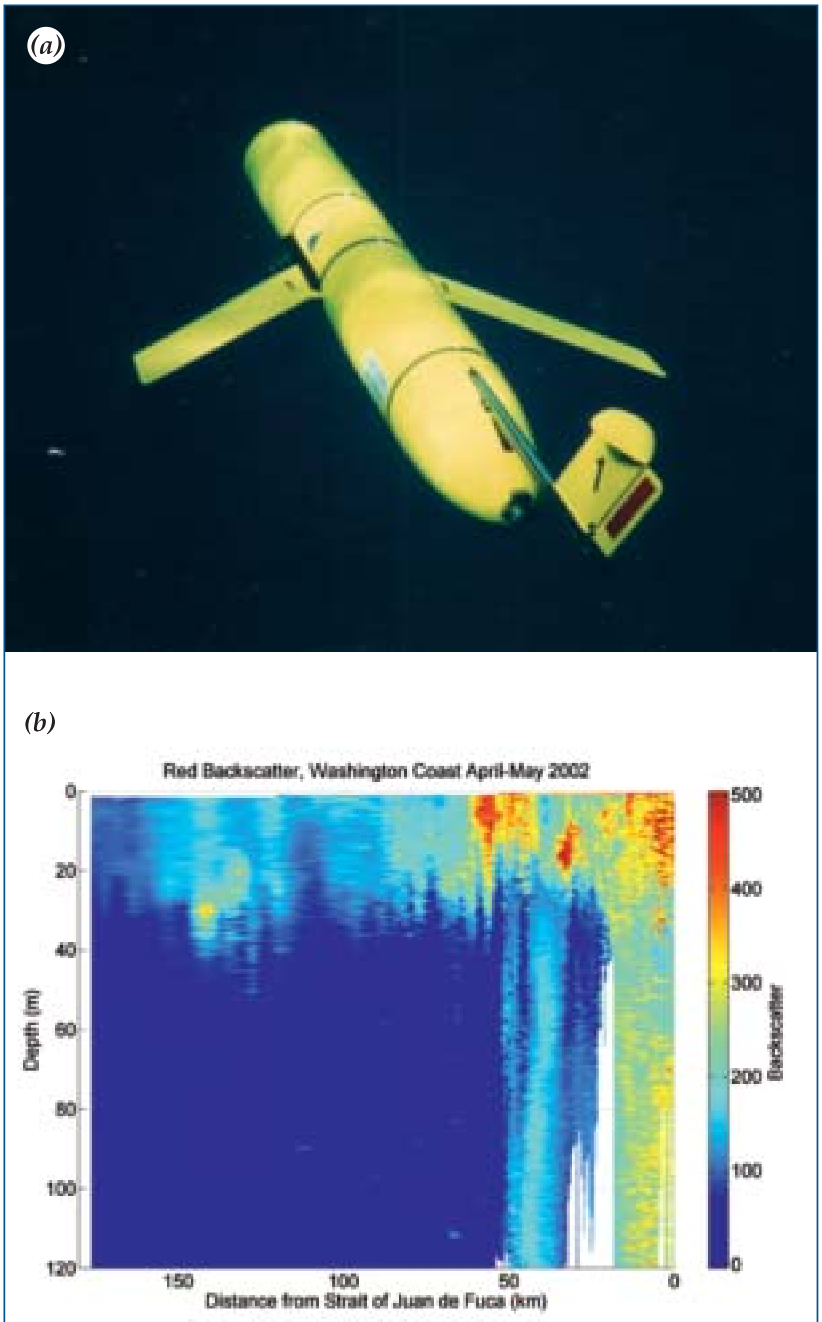

Figure 3. a) *The Slocum Glider, named after Captain Joshua Slocum, the first sailor to single-handedly sail around the world, was developed by Webb Research. During Summer 2003, fleets composed of 10 Slocum Gliders and 5 Spray Gliders operated for over a month in Monterey Bay in the most comprehensive demonstration of glider capabilities to date. (Solcum glider, David Fratantoni, Woods Hole Oceanographic Institution, by permission);* ***b)*** *A number of sensors have been successfully incorporated into gliders to measure temperature, salinity, pressure, chlorophyll, optical backscatter, and oxygen. Optical backscattering profiles collected during a Seaglider transect off the Washington coast in Spring 2002 were used to reduce the uncertainty in satellite-derived estimates of particle concentration, particularly in offshore regions with subsurface phytoplankton maxima. (Mary Jane Perry, University of Maine, and Charlie Eriksen, University of Washington, by permission.)*

Neutrally-Buoyant and Profiling Floats

The initial impetus for neutrally buoyant floats was measurement of subsurface currents, particularly the deep interior flows once believed to be too slow to be measured by mechanical current meters (Stommel, 1955). Swallow floats produced the first observations of energetic mesoscale flows (Swallow, 1955), leading to a fundamental change in our understanding of the ocean. Similar to surface drifters, water velocity is measured by tracking the float's position over time. The subsurface floats were tracked continuously with acoustics, with the floats acting as transmitters (SOFAR floats) or receivers (RAFOS floats). Autonomous profiling floats that periodically surfaced for Service Argos satellite telemetry of position and data were developed to enable global float coverage without reliance on acoustic tracking or the need to recover the floats many months after deployment. The current generation of profiling floats (Figure 2a) measure vertical profiles of temperature and salinity on each cycle (Davis et al., 2000). The existing (Figure 2b) and planned arrays of neutrally buoyant and profiling floats play a key role in understanding how circulation and properties in the interior of the ocean respond to climate change, and complement the deep-ocean moorings envisioned within ORION (see Clark, this issue). In the last few year several floats have been equipped with additional physical and bio-geo-chemical sensors. A float with a temperature sensor and three-channel radiometer was deployed for four months in the Sea of Japan to observe the evolution of thermal stratification (Figure 2c) and the phytoplankton spring bloom (Figure 2d); the capability to make such observations is critical to resolving the carbon cycle.

Underwater Gliders

The concept of a fleet of unmanned underwater gliders patrolling the world's oceans was put forward by Henry Stommel in 1989. Stommel's vision is becoming a reality today as gliders are being developed into a formidable oceanographic tool. Gliders, like floats, move vertically by controlling buoyancy (Figure 3a). Unlike floats, they also have wings that allow them to effect a horizontal movement, much like gliders in the air. They move forward through the ocean by alternatively diving (currently, as deep as 1000 m) and climbing in a sawtooth path,

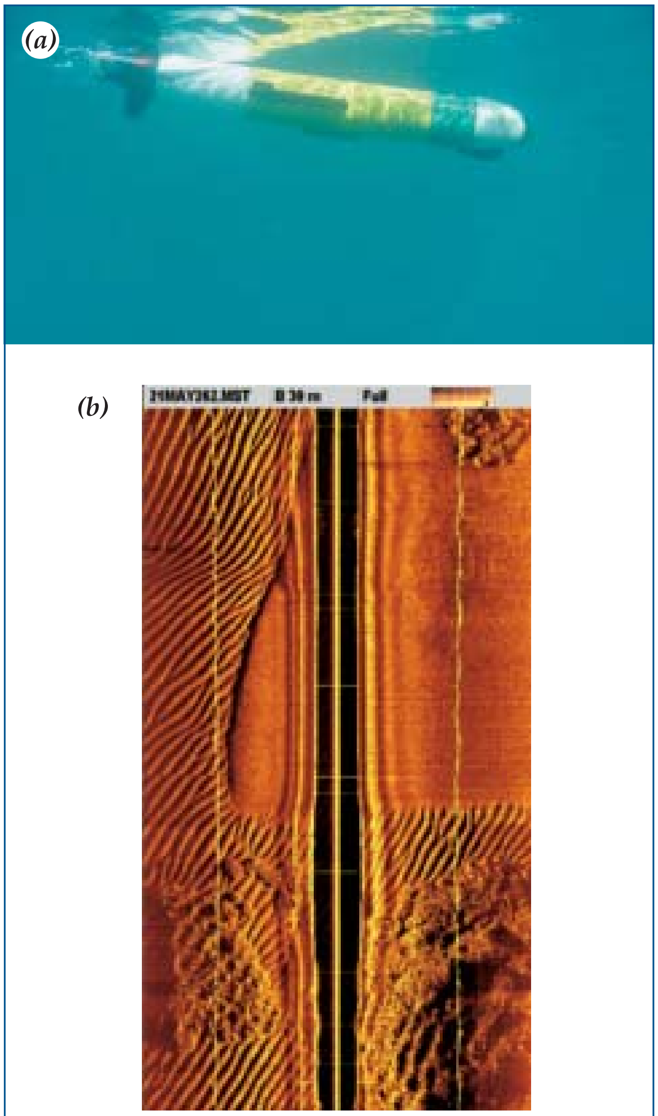

Figure 4. ***a)*** *The 1.6-meter REMUS, developed at WHOI, can operate for up to 20 h at 1.5 m s*$^{-1}$ *up to a depth of 100 m;* ***b)*** *A high-resolution acoustic side scan survey of bottom topography, carried out with REMUS in shallow waters off Framura, Italy, clearly shows details of sand waves with a 2.5-m period and the vascular plant* Posidonia. *(Dr. Christopher J. von Alt, Woods Hole Oceanographic Institution, by permission.)*

steering with rudders or adjusting their center of mass, much like a hang glider. Upon completion of every dive cycle, gliders report home. By following a sequence of waypoints, gliders produce a section survey, such as the chlorophyll section off the Washington coast (Figure 3b). By homing on a single target, gliders become “virtual moorings,” maintaining specific geographic positions and carrying out sampling in a profiling mode. Gliders can operate in either mode during the same mission. Although they are entirely autonomous and will follow a predetermined set of mission parameters, a feature of gliders is their flexibility—their mode of operation, trajectory, and other mission parameters can be controlled via two-way telemetry. Gliders were envisioned to provide long-term, low cost observations of phenomena that occur on longer time scales than are possible to observe with ships and on larger spatial scales than are possible to observe with moorings. Although glider technology is still in development, it is already apparent that the adaptive capabilities of gliders will contribute much to a sustained ocean observing system.

Autonomous Underwater Vehicles

Autonomous Underwater Vehicles (AUVs) are driven through the water by a propulsion system; as a consequence, they are the most maneuverable of all the autonomous platforms (for example, the REMUS AUV in Figure 4a). The origin of AUVs should probably be linked to Robert Whitehead who in 1866 is credited with designing, building, and demonstrating the first version of the Whitehead Automobile “Fish” Torpedo, a vehicle that achieved a speed of 3 m s^{-1} over a distance of 700 m. In the intervening decades, a number of AUVs of varying sizes have been developed and operated successfully in a wide range of applications in both the coastal and deep ocean. AUVs are controlled by an on-board computer; they can be programmed to swim at a constant pressure or altitude, or to vary their depth and heading as they move through the water to complete undulating survey patterns covering both vertical and horizontal swaths. They provide a highly productive means of performing seafloor surveys using optical or acoustic (Figure 4b) imaging systems. A diversity of physical, optical, acoustical, and chemical sensors have been used on AUVs in survey, float and loiter modes of operation. Sensor power is generally abundant on an AUV but the deployment time is relatively short, on the order of hours or days. With typical vehicle speeds on the order of 1.5 m s^{-1}, AUVs are especially effective for rapid surveys in dynamics coastal regimes, for racking a plume of a contaminant, or for carrying out routinely scheduled transects between coastal moorings. The potential for autonomous networking of AUVs, in which one vehicle passes information to a second vehicle via an acoustic line and the second vehicle then modifies its mission based on the information received, is particularly exciting for ocean observing systems. Such networking could enable features with high spatial variability to be accurately sampled and defined. These cooperative relationships exemplify the emerging potential of multiple vehicle operations and integration of multiple sampling modes in emerging ocean observation systems.

Potential for ALPS in the Ocean Observing System

It is difficult to envision an ocean observing system without ALPS. The well-established network of surface drifters in the open ocean and the growing Argos array of profiling floats already provide data critical to understanding ocean processes and their response to climate change. Gliders show great promise for contributing to data collection in the open ocean because they will be able to carry out systematic surveys for months at a time. The combination of surface drifters, profiling floats, gliders, and planned deep-sea moorings will provide an unprecedented opportunity to understand teleconnections in the open ocean. In the coastal zone fleets of gliders would provide a cost-effective mechanism for sampling large areas over long periods of time. They could be employed as movable arrays, alternating between the station-keeping, "virtual mooring" mode and the transect survey mode. The more maneuverable, faster AUVs would provide intensive sampling of smaller areas; with their larger payloads, they would provide a more comprehensive set of measurements. Both gliders and AUVs would contribute to reducing uncertainty in the spatial extent of properties measured by fixed moorings. Surface drifters and profiling floats modified for shallow water could also be employed in short-term studies, to provide additional spatial resolution. The various autonomous platforms and sensors each contribute unique coverage in the space/time domain, completing and enhancing the fixed arrays in an integrated ocean observing system.

Future Directions

ALPS technologies have progressed rapidly in recent years, and there is every reason to believe that significant advances will continue in the near future. The ALPS workshop identified several needs for more capable platforms. The various autonomous and Lagrangian platforms in development and use today are at different levels of maturity. In general, however, there is a need for increased reliability and endurance at lower cost. Driven by the desire to solve interdisciplinary problems, greater sensor payload is required on all platforms. Standardized interfaces between platforms and sensors would provide "plug and play" capability. Communications will be a continuing issue for widely distributed platforms, with increased bandwidth at lower cost the primary goal. A number of specific ideas for platforms arose in workshop discussions, for example: (1) a short-term, large, robust, recoverable float to carry newly developed sensors not yet ready for long-term deployment; and (2) a hybrid glider/AUV that combines the endurance of a glider with the speed and maneuverability of an AUV.

New sensors are needed across all the oceanographic disciplines. The unique demands of autonomous platforms are that the sensors be small and low-power. Already in active use are sensors to measure the standard physical variables temperature, salinity, pressure, and velocity. Biologically controlled optical variables such as fluorescence and transmission are seeing increasing use, with a number of additional sensors rapidly coming on line. To address carbon research, nitrate sensors have been developed, and their deployment on floats is imminent. Iron and trace metal sensors are sorely needed. Molecular biomedical and microsystems technologies are progressing independently of oceanography, making realistic future possibilities of deployment on autonomous platforms. Finally, the minimization of biofouling is an imperative for long-term deployment of almost all sensors.

Potential for ALPS in the IOOS

One of the strengths of ALPS is the possibility of deploying many relatively inexpensive units. The combination of all individual ALPS gives the observational network the ability to resolve scales and processes otherwise invisible. The network then takes on the trappings of a single large entity. The ALPS enterprise might then be appropriate for funding as a large facility, rather than as many small projects, as is typical now. Relevant issues are then how to continue appropriate technological development, and how to broaden community access to the best ALPS technology. A number of models were proposed at the workshop. Multi-PI (Principal Investigator) missions were endorsed as a means to bring together experts in platforms and sensors toward a common goal. For the more mature platforms, such as surface drifters, a commercial model of technology distribution may be appropriate. Centers of excellence acting in part as support facilities could be better suited to newer, more complex platforms, such as AUVs. In designing means of broader access, it is important to establish a reward system that recognizes the professional aspirations of scientists and engineers. The workshop recommended the establishment of an implementation group made up of technology originators and users to consider these issues in more depth.

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