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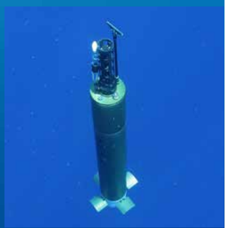


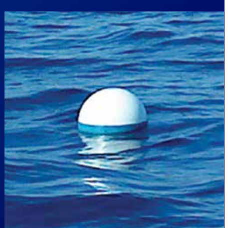

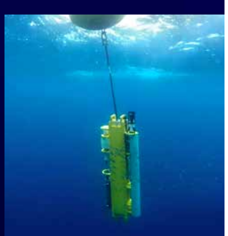

# Autonomous Instruments Significantly Expand Ocean Observing

## An Introduction to the Special Issue on Autonomous and Lagrangian Platforms and Sensors (ALPS)

By Craig M. Lee, Theresa Paluszkiewicz, Daniel L. Rudnick, Melissa M. Omand, and Robert E. Todd

Oceanography relies heavily on observations to fuel new ideas and drive advances, creating a strong coupling between the science and the technological developments that enable new measurements. Novel observations, such as those that resolve new properties or scales, often lead to advances in understanding. Physical, biological, and chemical processes unfold over a broad range of scales—seconds to decades and millimeters to ocean basins—with critical interactions between scales. Observational studies work within a tradespace that balances spatial and temporal resolution, scope, and resource constraints. New platforms and sensors, along with the novel observational approaches they enable, address this challenge by providing access to an expanding range of temporal and spatial scales.

Over a decade ago, the 2003 Autonomous and Lagrangian Platforms and Sensors (ALPS) Workshop (Rudnick and Perry, 2003) brought together members of the then-small community of ALPS developers and users to assess existing technologies, articulate high-priority science that could be addressed by systems that employed ALPS, and identify promising directions for platform and sensor development. At the time of the workshop, Iridium, a critical enabling technology, was in only its fifth year of operation, the Argo array consisted of roughly 900 floats (of its 3,000-float target), ocean gliders were developmental, and small, low-power chemical (oxygen, nitrate) and bio-optical sensors were just beginning to be deployed for extended periods on autonomous platforms. With a few notable exceptions, such as Argo, the Global Drifter Program, and the International Arctic Buoy Program, autonomous platforms were not widely applied to science problems. The ALPS report thus focused on describing promising science applications, including several ideas, such as observing boundary currents with gliders, the introduction of biogeochemical sensors to Argo, and autonomous platforms for sampling ice-covered environments, that have come to fruition and are described in the papers of this ALPS special issue of *Oceanography*. The workshop report noted that integrated systems composed of complementary platforms, including ALPS, ships, moorings, and remote sensing, would be needed to fully resolve the necessary spans of spatial and temporal scales. Recommendations for future development included larger, more capable floats, ALPS capable of collecting sustained measurements under ice, biological and chemical sensors, improved sensor stability and calibration protocols, and water sampling from ALPS.

Autonomous platforms advanced rapidly in the years following the 2003 ALPS workshop, fulfilling, at least in part, many elements of the vision articulated in the workshop report. A 2008 special issue of *Limnology and Oceanography* (Dickey et al., 2008) focused on ALPS accomplishments, and more recently Riser et al. (2016) and Rudnick (2016) reviewed the achievements of floats and gliders. The ALPS-2 meeting, held in February 2017 (see https://alps-ocean.us), engaged a broad community of developers and users to assess the state of ALPS technologies, review their accomplishments, and discuss the way forward. This issue of *Oceanography* attempts to capture a sampling of recent scientific, technological, and operational advances.

Floats have become workhorses for ocean observing. Argo has achieved global coverage with over 3,600 floats in the ice-free oceans, and includes deep and biogeochemical measurements (**Jayne et al.**). Diverse float technologies now include small, inexpensive air-deployable floats (**Jayne and Bogue**), water sampling and chemical analyses (**Bresnahan et al.**), rapid profiling of the ocean surface boundary layer (**ten Doeschate et al.**), and profilers that harness surface wave energy to conduct rapid, sustained sampling of the upper ocean (**Lucas et al.**). Bio-optical sensors are now routinely deployed on autonomous platforms (e.g., **Jayne et al.**; **Omand et al.**), with innovative analyses expanding the information that can be extracted from the resulting measurements (**Omand et al.**).

> "ALPS have evolved from developmental to operational, with recent achievements demonstrating their effectiveness as tools for ocean observing."

ALPS have proven particularly effective when used to create integrated observing systems capable of spanning a broad range of spatial and temporal scales. A system of drifters, floats, gliders, and autonomous surface vehicles, along with moorings, ship-based surveys, and satellite remote sensing, sampled in both mooring-centric Eulerian and float-following Lagrangian reference frames to investigate the processes that govern upper-ocean salinity (**Lindstrom et al.**). In the program described, ALPS defined the Lagrangian reference frame and provided sustained quantification of spatial structure around both the moorings and drifting floats. Drifters, floats, and gliders were used in the Arabian Sea to sample both boundary current variability and the small-scale dynamics that govern mixing and stirring in the interior basin (**Centurioni et al.**). Here, ALPS not only provided persistence and multiscale sampling, but also provided access to a region deemed to be too dangerous for ship-based sampling. Autonomous platforms tethered to drifting sea ice, sampling in conjunction with ALPS operating within the water column, have provided multimonth, sustained sampling of the atmosphere-ice-ocean boundary layer in the challenging Arctic seasonal ice zone (**Lee et al.**). Here, ALPS provided access to ice-covered regions; persistent sampling spanning melt to freeze-up; simultaneous sampling across atmosphere, ice, and ocean; and the ability to resolve the small-scale processes that govern sea ice evolution.

Patrolling gliders and air-deployed drifters and floats have targeted the paths of tropical cyclones, providing real-time measurements of subsurface temperature and salinity to constrain intensity and path forecasts (**Goni et al.**). Long-endurance gliders have been use for sustained, multiyear observing in coastal regions (**Pattiaratchi et al.**), marginal seas (**Jones and Kattan**), and western boundary currents (**Todd and Locke-Wynn**). Gliders provide persistent sampling of sections spanning hundreds of kilometers, with horizontal resolution of kilometers and temporal resolution of weeks, an excellent match for the dominant scales of many boundary regions. ALPS have also been used to mitigate risk, with gliders used to collect water column profiles over bottom-mounted acoustic Doppler current profilers in regions where trawling threatens instruments that reside in the water column (**Hall et al.**).

New platforms and sensors have expanded the utility of ALPS in novel directions. Long-endurance autonomous surface vehicles have been used to collect boundary layer measurements in challenging environments that include the Arctic (**Mordy et al.**) and the Southern Ocean (**Thomson and Girton**). Faster, shorter-range autonomous kayaks have sampled rapidly evolving small-scale variability in the Bay of Bengal and in the hazardous region near the calving fronts of ice sheets (**Nash et al.**). Turbulence sensors mounted on gliders have dramatically increased the spatial and temporal distribution of mixing measurements, facilitating new understanding (**St. Laurent and Merrifield**; **Rainville et al.**). Tagged marine mammals have emerged as a compelling approach for sustained collection of profiles in regions that are difficult to access, while also providing critical data about the animals themselves (**Cazau et al.**; **Treasure et al.**;

Roquet et al.; Rossby et al.). Powerful autonomous underwater vehicles (AUVs), guided by rigorously optimized search strategies, have been used to search for difficult submerged targets, such as Project Recover's efforts to locate the remains of US servicemen missing since the Second World War (Terrill et al.).

ALPS can exploit numerical models to inform strategies and guide sampling, while also delivering data for assimilation. Goni et al. and Todd and Locke-Wynn describe the impact of assimilating data collected by ALPS into forecast models, where the real-time data delivery, persistent sampling, and spatial distribution provided by ALPS make them valuable contributors. Nguyen et al. examine the impact of Arctic observations of ocean state estimates and use a model to assess the practicality and potential impact of profiling float deployments in the ice-covered Arctic. Lermusiaux et al. describe an approach for optimizing sampling constrained by both the desire to reduce uncertainty and the practicalities of choosing efficient, achievable flight paths. Thompson et al. detail recent efforts to automate glider sampling and path planning to better support deployments of large numbers of vehicles, while Kaeli advocates for co-robotic control that retains humans in the loop, and provides a summary-based mapping example of how decision-critical data might be transmitted to human operators using minimal bandwidth.

Beyond the sampling capabilities provided by ALPS, the achievements of the past decade point to the importance of the new operational modalities that they enable. Much of the efficiency provided by ALPS rests on their ability to exploit a wide range of deployment and recovery options, reducing dependence on dedicated research vessels. In addition to conventional operations from research ships, autonomous platforms have been launched from aircraft (e.g., Jayne and Bogue) and deployed from vessels of opportunity (Centurioni et al.), which facilitates distributed observing. Recent drifter, float, and glider deployments in a remote region of the North Pacific have been serviced by a modest, chartered sailboat (Lindstrom et al.). Autonomous platform deployments onto sea ice are often supported by aircraft that land on sea ice to shift personnel and equipment (Lee et al.). Sustained observing requires efficient, cost-effective operations. ALPS often achieve this by relying on local logistics, where modest investments in training can provide responsive, flexible operations at low cost.

ALPS have evolved from developmental to operational, with recent achievements demonstrating their effectiveness as tools for ocean observing. The persistence and scalability of autonomous approaches provide the ability to sample regions of the spatial and temporal spectrum that have previously been difficult to access. Integrated systems that include ALPS, moorings, ships, and/or remote sensing can resolve multiscale processes and support investigations at the interfaces between disciplines, sampling ocean, atmosphere, and ice dynamics and their interactions with ecosystems and biogeochemistry. The efficiencies provided by ALPS also make them promising tools for climate-scale observing, where inexpensive approaches with simple logistics are required to sustain critical measurements over decades. In addition to advancing capabilities, future ALPS developments might focus on platform efficiency, including efforts toward improved reliability and ease of use. Sensor calibration and cross-calibration grow in importance with the deployment of large numbers of autonomous sensors and the use of new instruments for measuring biological and biogeochemical parameters. Sensors for oxygen, nitrate, pH, and a range of bio-optical properties are being deployed widely, but the need for additional small, efficient sensors for biological and chemical parameters remains.

As the articles in this special issue of *Oceanography* witness, ALPS have already logged significant scientific and operational achievements, and they promise exciting developments stretching into the future.

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