# TOWARDS NEW PLATFORM TECHNOLOGY FOR SUSTAINED OBSERVATIONS

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***ABSTRACT*** *- Affordable platforms underpin our ability to make sustained in situ observations of the ocean. Autonomous vehicles, such as drifting and profiling floats, already complement research, survey and voluntary ships. Floats are but one, more mature, member of what can be considered a family of autonomous platforms. The more recent additions to the family include moored profilers, autonomous surface craft, gliders and propelled autonomous underwater vehicles. Research communities of scientists and technologists are rapidly gaining experience of these newer vehicles, building on the proven attributes of today's technology. This experience will provide a firm foundation for the introduction of new platforms into the arena of sustained observations.*

## 1. INTRODUCTION

Ocean observations rely on platforms and sensors. Programmes of sustained observations naturally place a greater emphasis on affordability and reliability than on pure technical innovation. Historically, innovative platforms and sensors have been proven during short-duration process studies or other limited experiments. But we are in a period of change. Platforms are now being built specifically with sustained observations as a design goal and with cost per profile or per kilometre as a key specification. In addition, *in situ* observations, in themselves, are but one facet of an observing system; their systematic integration with remote sensing data and numerical simulation models is becoming the norm.

The purpose of this paper is to review the current thinking on how science needs influence and guide new platform development; to couple platform development to the often separate but symbiotic developments in sensor technology; to discuss key developments in autonomous vehicles (profilers, gliders, powered vehicles), very much in context of platforms that are already contributing to routine (if not sustained) observations. Perhaps the developments in chapters 3-5 of this paper will contribute to sustained ocean observations over the next decade - beyond, some of the ideas in chapter 6 may come to fruition. Improved energy storage methods will drive down costs, as will new generations of satellite communication systems. For some vehicles the emerging needs of offshore oil and gas companies may make for a larger market and may help reduce costs.

Docking systems, already demonstrated in shallow water, will enable autonomous data gathering between moorings. Those moorings may utilise wire-guided profiling vehicles with megametre endurance for gathering physical, biological and chemical variables. In addition, the moorings could provide data-transmission and battery recharging facilities for the autonomous vehicles.

Progress is not limited to oceanographic autonomous vehicles. Autonomous aircraft (for example, the Aerosonde) are already capable of operating over ranges of 2500 km, a range that is set to double each year over the next 2-3 years. With sensor suites measuring temperature, pressure, humidity and wind autonomous aircraft have a clear role to play in marine meteorology.

Prior to the sustained use of advanced technology vehicles, their reliability and methods of integration into an operational system will need to be proven. Parallel developments in data-handling infrastructure will be required if the integrity of the information is to be assured.

The paper ends with a brief note on the legal aspects of autonomous vehicles. We live in an era where technical innovation far outpaces progress in matters of international law. While this should not be seen as restrictive, an awareness of the issues is important, especially for a global integrated observing system.

## 2. THE NEED FOR AUTONOMOUS OBSERVATIONS OF CLIMATE

Fifty years ago the interior ocean circulation was perceived as sluggish and essentially steady. As accurate direct velocity observations became available from early moorings and neutrally buoyant Swallow floats it became clear that much of the ocean was populated by energetic mesoscale eddies with scales of O(30 days) and O(100 km). At about the same time Jerome Namias and colleagues noticed that large-scale variations of routinely observed sea surface temperature (SST) in the North Pacific persisted for months and seemed to be associated with changes in the seasonal climate of North America. These two observational discoveries were the origins of both the motivation for global ocean observations for climate and the understanding that observing ocean climate variability would require substantial sampling to separate climate variability from other variability with smaller space and time scales.

The 1980's brought an understanding of the processes involved in the coupled ocean-atmosphere El Nino / Southern Oscillation (ENSO), an awareness that this phenomenon affected climate over much of the globe, establishment of an observing system including the ambitious TAO array to monitor the equatorial evolution of ENSO and the development of climate forecasts with significant skill at ranges near one year. At the same time there was an increasing awareness that anthropogenic climate forcing by changes in the composition of the atmosphere resulting from energy consumption, industrial production and changes in land use might lead to significant climate change. The long time scales of the phenomena involved in anthropogenic climate forcing and the fact that it has no parallel in the paleoclimatic record makes an empirical approach impractical and forces a heavy reliance on dynamical models. This reliance requires us to determine how to verify the ability of these models to predict a response that has never been observed.

One strategy for verifying models of anthropogenic climate change is to use quantitative observations of both the state of today's climate and the processes that maintain that climate as benchmarks for models and to simultaneously insist that the models simulate the major modes of observed interannual to decadal climate variability.

The diversity of climate phenomena, from seasonal-to-interannual predictability of ENSO through decadal variability of the North Atlantic Oscillation and the Pacific Decadal Oscillation and on to rapid climate change and anthropogenic forcing means that the ocean observing system for climate must be designed to detect a wide range of signals in the face of competing high-frequency noise. Even if one sets aside the critical short-term exploratory and process-oriented studies needed to clarify specific phenomena to be included in models, the observing system must deal with a broad range of processes shaping the ocean's role in climate and must do this over the globe and the full oceanic water column. While SST may be the only oceanic parameter that significantly affects the atmosphere, to predict SST or understand its variability requires understanding all the oceanic processes that affect SST on the time scale of concern.

When considering climatic responses to anthropogenic forcing, and the potential for rapid climate shifts, the very long time scales of importance bring the entire wind-driven and thermohaline circulation into play. This means that the climate observing system must include ways to monitor processes in the harsh, high- latitude winters as well as interactions with sea ice and transport processes at great depth. At the same time other models suggest that substantial climate shifts can be caused by changes in the tropics modulating the evolution of ENSO-like cycles. Thus to address response to anthropogenic forcing all latitudes and depths must be observed, albeit perhaps at a slower rate than required for the tropical upper ocean.

Even the assertion that slow climate drifts can be understood by observing only low-frequency variability may be an oversimplification. The role of eddies in modulating the general circulation has long been an issue and recent work in the subtropical North Pacific suggests that slow variability of the aggregate affect of mesoscale eddies or Rossby waves may be important in understanding climate variability in the ocean.

Data assimilating models will be essential to integrating the necessarily sparse satellite and *in situ* observations needed to integrate observations from the future observing system. Nevertheless it will be some time before these models and our knowledge of what ocean processes are central to climate are adequate to design the ultimate ocean climate observing system. This design must rely on our best estimates today and the flexibility to adapt to new knowledge. There are, however, at least three things that are certain about the design:

1) Global observations from all depths at a density higher than today's and sustained for many years will be required to separate climate processes from each other and from the noise of regional phenomena and mesoscale variability in order to diagnose the climate's dynamics. Simply marking the climatic changes of a few key parameters will not do. This means massive near-real-time observations from around the global ocean assimilated within the most sophisticated numerical models. Satellite remote sensing naturally provides the needed temporal and spatial coverage but numerous *in situ* observations will be needed if the internal structure of the ocean is to be observed.

2) Implementing such a system will be expensive and unless every economy afforded by new technology is used it will be too expensive to happen. Sophisticated measurements will still need to be taken from research ships but the vast volume of data must come from remote sensing and *in situ* systems designed to deliver voluminous accurate measurements at minimal operational cost.

3) Unless the flexibility to respond to new understanding of climate dynamics is built into the observing system it will soon be obsolete. Similarly, if the observing system is too finely tuned to today's conventional wisdom it may fail discover anything new.

It is within this framework that we feel autonomous vehicles present great promise for evolution of a global ocean observing system for climate. Recent developments in digital signal processing, satellite communication, miniaturisation of mechanical components and sensors are making possible a new approach to gathering climate data from autonomous platforms. A new generation of stable, low-power sensors to measure not only parameters of physical interest, but properties describing chemical and biological ocean processes, promises to make these platforms useful to the broad oceanographic community concerned with all aspects of climate phenomena.

## 3. SENSORS FOR USE ON AUTONOMOUS PLATFORMS

During the past decade, there has been a major thrust forward in sensors, which are capable of providing important chemical, optical, biological, and acoustical as well as physical data [Dick 91]. Interdisciplinary sensor suites are important for studying problems such as carbon dioxide cycling and variability, the role of biology in upper ocean heating, phytoplankton productivity, upper ocean ecology, population dynamics, and sediment resuspension [Tokar 99]. Many of the new sensors are relatively small and have modest power requirements. Thus, the deployment of an increasing number of these sensors from autonomous platforms is becoming practical.

Moorings have been used to obtain chemical, optical, biological and acoustical data in addition to the more common physical data and have proven to be excellent platforms for testing and developing new sensors. A few examples of variables which can now be sampled from moorings include: nitrate concentration, dissolved oxygen, partial pressure of carbon dioxide, scalar irradiance, spectral inherent and apparent optical properties, chlorophyll fluorescence, and size distributions of particles and zooplankton. Most variables can be sampled every few minutes.

Already, new scientific insights into interdisciplinary processes have resulted from concurrent, multi-sensor measurements from moorings [Dick 98]. Examples include: the roles of seasonal and episodic forcing and eddies in increasing upper ocean nitrate and levels of primary productivity at mid- and high-latitudes; monsoonal atmospheric and eddy forcing of productivity in the Arabian Sea; modulation of productivity in the equatorial Pacific through tropical instability waves, Kelvin waves, and El Nino/La Nina sequences; sediment resuspension via internal solitary waves and hurricanes; and variability in upper ocean heating caused by phytoplankton. Moorings are also being used to groundtruth ocean colour data collected from satellites. Durations of interdisciplinary moorings have typically been a few months to a year. The major constraint remains biofouling. However, new anti-biofouling methods are being developed and tested; encouraging results suggest that this impediment will be considerably less limiting in the future.

Drifters, and most recently autonomous underwater vehicles (AUVs), have also been used to collect limited interdisciplinary data sets. Size and power are more constraining parameters for drifters, AUVs, floats and gliders than for moorings. Nonetheless, some optical and chemical sensors have been successfully deployed from drifters and plans are underway for float and glider applications. AUVs have already carried similar sensor suites as well as ADCPs and turbulence probes. Again, biofouling will be problematic for long-term measurements from these various platforms.

In the future, it is likely that continued expansion will occur in the areas of small, energy efficient, interdisciplinary sensors. In particular, sensors will likely be capable of measuring a much wider range of chemical compounds and trace elements [Toka 99], higher spectral resolution inherent and apparent optical properties and spectral fluorescence, and multi-frequency acoustical systems for better resolution of zooplankton size classes. Cost per sensor is an important issue and may be a major limiting factor, especially for expendable platforms. Commercialisation of key sensors will be essential for this reason.

Telemetry of data from the various platforms is critical for many, if not most, new applications. Future low earth orbit (LEO) satellite systems should greatly expand bandwidth and enable transmittal of much greater volumes of data. The synthesis of *in situ* interdisciplinary data with satellite-based remotely sensed data sets has already allowed improved interpretation and utilisation of both. Efforts are now underway to develop data assimilation models which will utilise near real-time, autonomously collected, *in situ* and remotely sensed, interdisciplinary data sets. The sensor and telemetry technologies mentioned here will be important for maximum utilisation of the various platforms described in detail in this paper.

## 4. EXISTING TECHNOLOGY FOR SUSTAINED OCEAN OBSERVATION

Traditional methods of making sustained observations of the ocean's interior include: shipboard profiling and sample collection, deployment of moored arrays of internally recording instruments, use of cabled (to shore) sensor arrays and deployment of various types of drifting buoys. These methods are generally viewed as inadequate and/or too costly to meet the future societal needs for continuous real-time observations at many locations throughout the world's oceans. Shipboard measurements will continue to play a critical role in oceanographic science, but the cost of oceanographic research vessels (€/$ 20,000 and up per day) preclude their use for continuous observations at fixed sites. However, commercial ships that routinely transit fixed routes do offer a cost-effective means of doing repeated surveys across ocean basins. To date, ship of opportunity programs have been limited to XBT and ADCP profiling from a limited number of vessels. An opportunity exists in the oceanographic instrumentation community to develop highly automated remote sensing and expendable profiling systems for use on ships of opportunity to routinely and continuously sample broad reaches of the oceans. The critical elements needed in such a development program are improvements in the sensors that can be used in this kind of environment and fully automated systems that do not impact normal vessel operations. Such standalone sensor systems should also be capable of operating on many different types of vessels.

Moored arrays of internally recording instruments have been the mainstay of efforts over the last 30 years to observe ocean variability and to gain insight into the forces driving ocean circulation. However, the cost of traditional moored arrays (typically of the order of €/$ 200,000 in the deep ocean including instrumentation, supplies, labour and shiptime) is effectively limiting their application to specific high interest locations for relatively short (one or two year) time periods. To play a significant role in sustained global observational programs, moored arrays need to be enhanced in two areas. First, they need to be engineered to operate for extended periods (perhaps 5 years or longer) without maintenance. Present systems are typically maintained at 6 month (surface moorings) to one or two year intervals (subsurface moorings). Second, they need to automatically transfer data to shore so that the data is available on a reasonable schedule. If these two goals can be achieved at a reasonable cost, then an extensive grid of moored arrays would be a feasible and cost effective part of a global observational system. Researchers are presently designing a prototype mooring system for making low frequency current and temperature measurements with the requisite features, i.e. 5-year life and data telemetry [Hogg 98].

Cabled sensor systems are an ideal way to continuously observe the ocean. They are reliable for many years, offer high bandwidth telemetry, provide almost unlimited power for sensors, and are inexpensive to operate once installed. Unfortunately, most oceanic sites are so far from shore that cables are prohibitively expensive to install. In areas where cables already exist, such as along abandoned telephone cable routes, there is an opportunity to utilise their bandwidth and power delivery for reasonable cost. Prototype systems that take advantage of abandoned telephone cables are being developed [Chav 97]. This approach is of course limited by the availability and location of existing cables.

Drifting buoys and floats have always been a cost effective means of collecting data over broad oceanic areas and the new generation of profiling drifters is enhancing the quality and quantity of data that can be acquired with this technology. As low power satellite telemetry options improve the quantity of data available should increase substantially. The limiting technology for profiling drifters is probably sensor technology, see section 3.

## 5. EMERGING TECHNOLOGIES

### 5.1 Profiling floats

Planned global coupled ocean-atmosphere models will be able to improve their forecasting skill by assimilating 3D ocean *in situ* observations. An important source of these 3D *in situ* observations will be profiling floats. Historically, floats have been deployed as Lagrangian drifters and the ARGO proposal [Argo 99] calls for a significant increase in the number of floats deployed in this mode. A complementary method of deployment will enable profiling at fixed locations [Marc 99].

#### *5.1.1 Lagrangian systems*

Subsurface drifters were deployed in significant numbers during the WOCE experiment. ALACE and MARVOR floats have contributed (and continue to contribute) to our knowledge of ocean circulation and processes. They deliver mainly undersea trajectories: precise trajectory of watermasses for the acoustically tracked MARVOR, and mean trajectory for the ALACE positioned by ARGOS when surfacing periodically. Profilers were naturally derived form those drifters: the P-ALACE [Davi 98] and the PROVOR [Loae 98] which are increasingly used in scientific experiments. But these instruments suffer from some deficiencies that need to be overcome before we have profilers usable on a routine basis in global observation networks:

- They are presently deployed by research vessels and scientists. They will have to be deployed by non-specialists from ships of opportunity and aircraft as it is presently done for meteorological drifters. Design and initial experiments are now in progress.
- The commonly used one-way satellite communication system limits transmission of data when selecting 80 to 100 (T-S-D) points from a typical 2000 m profile. In addition, the transmission time requires the float to be on the surface for 6 to 20 hours. Two-way communication systems offering a large increase in data throughput are becoming available.
- The salinity sensor has to be improved in order to give accurate data during the 4-year lifetime of the float (see section 3).
- Obviously, it is desirable to decrease the unit cost of profilers. The needs of ARGO (3000 floats at sea) will spur several manufacturers to compete on price and performance.

### *5.1.2 Eulerian systems*

Eulerian measurements are an important complement to the Lagrangian ARGO network. Several techniques can be employed to provide these Eulerian measurements including gliders as virtual moorings (section 5.2.1) and moored profilers (section 5.3). One can also imagine using the Lagrangian multicylce profiler in a psuedo-Eulerian way: the float lying on the bottom between an up and down vertical profile. Pop-up expandable instruments are also good candidates. One can observe that the meteorological observation network is mainly constituted of expendable radiosondes profiling the atmosphere twice a day in 700 places all over the globe.
As an example of a current development, expendable pop-up system (EMMA) under development has the following characteristics [Cono 98]:

- Expendable lighter-than-water probes, equipped with CTD and other sensors profiling the water column from the bottom (5000 m) to the surface and, after surfacing, transmitting the data recorded during ascent through the ARGOS link;
- Probes may be dropped from vessels or aircraft and stored on the sea bottom until released by timer. During storage, the probe sensors are encapsulated as protection against fouling, immersed in a standard solution for recalibration before popping up. A very high quality of measurement is expected.
- A platform operating a number of such probes moored at the same location, with probes released sequentially, is a generator of pre-programmed time series of profiles at predefined geographical co-ordinates.
- The marginal cost per probe is estimated to be less than €/$ 1000 in production quantities.

## 5.2 Gliders

Inadequate sampling is the fundamental problem for ocean observations, be they physical, chemical, or biological. Oceanographers continue to be frustrated in trying to distinguish between temporal and advective changes in the ocean interior because they are unable to measure densely enough in space and time, being limited by the cost or depth range of conventional methods (ships, moorings, and satellites). Glider technology is intended to answer the need to observe the ocean at more places, more often, and for longer periods than is affordable using traditional platforms. Gliders embody the philosophy that a distributed network of smaller, smarter, cheaper platforms is the most cost effective way to observe vast regions of the ocean.
Henry Stommel [Stom 89] dreamt of a global fleet of autonomous vehicles travelling long distances while telemetering temperature and salinity profiles via satellite to ground control stations. Davis *et al* [Davi 92] took a large step in realising this dream by developing ALACE floats, vehicles that profile vertically under buoyancy control while drifting horizontally. Gliders use wings and hydrodynamic shape to induce horizontal travel from buoyancy control. The key elements making possible long-range gliders are efficient buoyancy control, modest hydrodynamic performance, low power electronics, on board computing, satellite navigation and two-way communication for near real time data transmission and remote control.
Gliders are autonomous underwater vehicles designed to observe the ocean interior with adaptive sampling control over long ranges at much lower cost than is possible with ships or moorings. Unlike gliders in the atmosphere, they glide both down and up by making themselves alternately more and less dense than the fluid through which they travel. By assimilating Global Positioning System (GPS) navigational fixes obtained at the sea surface, they set an underwater course to reach an intended target. By gliding to a sequence of targets, they may be controlled to execute a survey. By homing on a target, they can profile vertically at a selected geographic location, imitating the sampling of a moored profiler. Through two-way communication at the sea surface, they can be controlled remotely to observe at arbitrary locations in near-real time. By virtue of remote control, they can be recovered and reused. Those now under development are small enough to be launched and recovered from small boats, largely obviating reliance on ships. Battery operated gliders now being tested have design ranges measured in thousands of kilometres and operational duration

measured in months or years. In regions where it is sufficiently large, thermal stratification may be used to greatly augment glider range [Webb 99].

While research ships may cost ~ €/$ 20,000 daily to operate, moorings ~ €/$ 200,000 per deployment, and satellites ~ €/$ 200,000,000 per mission, the potential operational costs of gliders are much less. Amortising the construction cost of a glider into 5 missions brings the cost of a surface to ~2 km depth CTD profile to ~ €/$ 20, comparable to the cost of an XBT probe alone (exclusive of the ship and data collection costs). Gliders are inexpensive enough that loss of individual units is not catastrophic. That is, an array of gliders is reasonably fault-tolerant, both because of comparatively low unit cost and the ability to adjust a sampling plan in response to failures.

Traditional oceanographic surveys follow fixed pre-selected transects and are seldom modified during their executions because of constraints on cruise duration. Moored data are perforce collected where the moorings are set. Data-adaptive sampling is relatively new in oceanography and has been associated generally with short duration, limited extent surveys because conventional AUVs have ranges and duration measured in tens of kilometres and hours [Zhan 99]. Because of their modest cost and long range, gliders can perform data-adaptive sampling over much more extended durations than otherwise feasible.

Gliders are now under development by three groups in the U.S. (Scripps Institution of Oceanography/Woods Hole Oceanographic Institution, University of Washington, and Webb Research Corporation). Those now being tested are ~50 kg devices 1-2 m long, designed to operate from the ocean surface to ~2 km depth at speeds ~0.25 m/s with power consumption of ~0.5 W. They use ~1N buoyancy force to alternately dive and climb, requiring volume changes of ~0.2 L. Gliders dead reckon underwater, controlling pitch and roll trim (used to turn) by shifting mass within the vehicle. In battery powered vehicles, volume change at depth is accomplished by pumping oil from an internal reservoir to a bladder external to the vehicle pressure case. Roughly three quarters or more of the energy used by battery powered gliders goes to run the pump. With lithium battery packs of several kg, gliders are capable of several hundred dives to 2 km depth in a mission, hence profiling vertically through a couple of thousand km.

Low hydrodynamic drag together with substantial lift from wings is crucial to glider performance. Gliders now being tested are capable of gliding along slopes from as steep as 2:1 to as gentle as 1:5. A range of possible slopes allows a glider a range of possible horizontal speeds and a range of power usage for a given vertical speed. The gentle glide slopes attained by vehicles now being tested imply horizontal ranges of several thousand km. All of the ocean is within 2700 km of land, a small percentage being farther than 1500 km away, so that gliders typically may need only to devote a fraction of their energy reserves to transit from land to a region of interest and back.

Global two-way communication using hydrodynamically unobtrusive antennas and low power transmitters is crucial to glider operation. Commercial systems promise faster (~2 kbps) and less expensive (~€/$ 0.10-10.00/kbyte), two-way communication. Fast data transfer is necessary for gliders to stay at the surface only for a few minutes.

Instrumentation carried by gliders is limited by power, hydrodynamic drag, and cost. Gliders now carry CTDs whose accuracy is comparable to those lowered from ships. The additions of dissolved oxygen and optical sensors are under development. The attractiveness of making gliders measure multiple ocean variables has to be balanced against the virtue of cost control.

### *5.2.1 Gliders as virtual moorings*

Gliders are constrained by energy considerations to move through the ocean at speeds comparable to ocean currents. Transects made by them are necessarily more prone to aliasing by temporal variability than are conventional ship-based sections. One way to use gliders is to control them to maintain their geographic position by stemming the ambient currents. As long as the depth-averaged current is weaker than the maximum horizontal speed a glider is controlled to attain, a glider can maintain its position while profiling vertically. In this mode, gliders can collect time series of profiles much as a moored profiler does, yet with two orders of magnitude less total mass

and without the need for a ship to deploy and recover it. The ability of gliders to transit to arbitrarily chosen locations makes possible intercomparison to monitor sensor drift.
Virtually moored gliders can be expected to maintain their positions as well as or better than a surface mooring does. They use the difference between successive GPS fixes and the displacement predicted by dead reckoning to estimate horizontal currents averaged over the depth range of glider profiles. In addition to temperature and salinity profiles, then, gliders can be used to collect transport time series. In principle, pairs of virtually moored gliders can be used to estimate absolute geostrophic currents by adjusting geostrophic shear to fit depth-averaged current. A network of gliders could be used to solve the geostrophic reference problem regionally or globally, depending on the scale of the array.
Establishing a relatively sparse global network (~1000 km separation) of virtually moored gliders is likely to be a cost-effective solution to the problem of monitoring upper ocean climate. The approach is opposite to that used by hydrographers to estimate the large scale slopes of property surfaces. Instead of resolving mesoscale eddies and fronts with closely spaced depth profiles along long transects, a network of virtually moored gliders would resolve variability temporally, including tides and internal waves, to estimate lateral gradients by differences over comparatively large distances. Variance in such quantities as dynamic height contributed by higher frequency fluctuations (e.g. tides, internal waves) is comparable to that contributed by mesoscale fluctuations in many oceanic regions. A global network of hundreds of gliders would be capable of providing an Eulerian description of upper ocean climate signals at modest cost.

#### *5.2.2 Repeated glider sections*

A majority of what we know about ocean circulation has come from hydrographic sections taken from research vessel such as those that carried out WOCE sampling. The repeated hydrographic sections from which it would be possible to study climate variability are extremely. Recent developments allow Voluntary Observing Ships (VOS) to deploy XBT and XCTD probes at high enough density that transports can be accurately calculated over the upper 2 km and it is feasible to repeat such VOS sections several times per year if there is sufficient shipping.
Although gliders move much slower than ships they provide an opportunity for repeated section measurements to observe both variability of property distributions and of the lateral heat and water property transports that drive the ocean climate engine. It is relatively simple to outfit gliders with CTD sensors that have precision and accuracy equal to (in the case of temperature) or superior to (for conductivity and depth) those of expendable probes. Gliders are most efficient when used in the upper 2 km, like VOS probes, but the section location and timing need not be tied to shipping and could be adapted to the conditions observed. Additional sensors suitable for glider installations and capable of observing chemical and biological variability along a section are also available.
While long-range performance has not yet been demonstrated, it is feasible for a glider to operate at a speed near 25 cm/s over a range of the order 5000 km; longer ranges are feasible at reduced speed. This is much too slow to consider a glider section to be synoptic but is, in many places, sufficient to adequately measure the along-track gradients needed to compute transports. By using altimetric and surface temperature measurements inside a model framework, it may be possible to extend this capability to relatively strong currents in which the propagation of variability features is relatively simple.
The most straightforward use for gliders operating in section mode may be in within 1000 km of coast locations to observe the physical and biological manifestations of climate variability. Here gliders could be repeatedly launched and retrieved without use of ships allowing accumulation of long time series of repeated sections at very low cost.
In the final analysis, the balance of autonomous sampling from floats that are carried by currents, gliders in virtual-mooring mode which hold position against the currents and gliders which operate along sections will depend on both the phenomena to be measured, the overall density of observation that can be afforded and the nature of the noise which obscures the signals of interest. If the observational density is high enough or the signal has large enough scale that it is fully resolved,

then all methods are equal. In low density, the ease of interpretation might favour a virtual mooring where spatial variability does not confuse interpretation. In a low noise environment it may be efficient to sample several locations with one glider (sections) while in a high noise environment sampling may need to be confined to a single location (virtual mooring) to keep the signal to noise ratio high. In a region with large spatial variation a virtual mooring may be aliased by spatial variability whereas a glider section will be aliased by temporal variability if it is large.

### 5.3 Moored profilers

Less revolutionary than virtual moorings, moored profilers have great potential for providing cost-effective and very detailed ocean observations over extended time periods. Essentially, a moored profiler is an AUV that is tethered to a mooring line so as to restrict its range of motion to two degrees of freedom: vertical travel along the wire and rotation about it. Thus in comparison to AUVs and gliders, far simpler control systems may be employed. While moored profilers do require the added expense of conventional mooring components, i.e. anchors, wire rope, buoyancy and a ship to deploy, service and recover, these moorings are very simple in design and do not add a great deal to the overall system cost. Unlike virtual moorings, moored profilers are able to operate in most current regimes and in areas where surfacing is not an option (such as in ice-covered seas). The key to the effectiveness of moored profilers is their ability to carry a single suite of sensors as they make repeated profiles of the water column. Thus, moored profilers are ideally suited for "time-series stations" within sustained ocean observations programs, but are also well matched to short-term, process-oriented experiments that require information at high-vertical and temporal resolution.

Moored profilers were developed by several investigators in the past and new designs are being actively pursued by several groups at this time. The best known examples of the previous generation of profilers include the Cyclesonde developed by Van Leer [Leer 74], the Profiling Current Meter (PCM) developed at Draper Laboratory [Erik 82] by Eriksen and Dahlen, and the current-driven profiler developed by Eckert and Morrison [Ecke 89]. Though each of these instruments provided unique views of ocean variability, none of these earlier systems had the kind of general utility that the more recent designs have, and none are being produced commercially at this time. Groups actively working on the next generation of moored profilers include Brooke Ocean Technology [Fowl 97], who are testing a wave-driven profiler for coastal waters, Provost and du Chaffaut at Universite Pierre et Marie Curie, Paris [Prov 96], who have a prototype buoyancy driven device capable of cycling to 1000 m, and McLane Research Laboratory, who are the licensed commercial builder of the WHOI traction-drive profiler. It should be noted that the McLane profiler, while similar to the WHOI-developed system described below, has significant mechanical differences from the WHOI unit in terms of improved payload and lower hydrodynamic drag characteristics.

To introduce the capabilities and limitations of this class of oceanographic instruments, we describe here the WHOI Moored Profiler [Dohe in press], which is in the advanced prototype stage. The profiler is an oblate spheroid 0.8 m in diameter and 0.4 m thick. To move along the mooring wire, the profiler utilises a small DC motor and traction wheel. Profiling at about 30 cm/s, the drive system draws about 1.7 W from the battery. About 50% of this energy is used to overcome hydrodynamic. One million metres of profiling is possible over deployments of a year or more using a lithium battery.

The present sensor payload of this profiler includes an FSI Micro-CTD and 3D-ACM 3-axis acoustic current meter. A new generation CTD is being developed at FSI that will reduce power consumption from 1.5 W to less than 0.5 W, which should increase profiling range to more than 1.5 million metres. While not yet a standard implementation, real-time telemetry methods have been developed which allow moored profilers to transfer their data to shore in near real time. These methods include inductive data transfer via the mechanical mooring wire and acoustic data transfer from an acoustic transmitter in the profiler to an acoustic receiver in the surface buoy.

Moored profilers built at WHOI have cost about $70,000 including the CTD and current meter. Simple moorings using wire rope with a single steel buoy for buoyancy add about $20,000 to $25,000 in expendable materials and labour per deployment. These numbers are probably representative of the first generation of commercial profilers as well. If these profiler costs are amortised over 5 or 10 deployments and we assume an instrument endurance of 1.5 Mm per deployment, then an equivalent cost per 2000 m profile to the one suggested in Section 5.2 for gliders (i.e. $20) would be in the $40-$50US range (but would include velocity as well as temperature and salinity data. Future development ideas include extracting energy from wave-induced mooring motion (as the Brooke Ocean device now does for vertical motion), extending the operating window of profilers to the surface, and increasing the sensor payloads to include biological, chemical and optical sensors. Since profiler payloads are not strongly limited, this latter task is not particularly daunting though power consumption by the sensor payload remains a major issue, as does biofouling for some types of sensors.

The primary advantage that moored profilers have over traditional moorings with discrete instruments is that they are capable of collecting higher quality data with higher vertical resolution at lower cost. A single suite of instruments on a moored profiler can replace 5, 10 or even 20 individual instruments on a traditional mooring. This can lead to substantial cost savings in terms of capital costs for instruments and recurring costs for instrument maintenance and calibration. Data quality may be improved because multiple calibrations are not needed to compare data from different instruments. The primary disadvantages of moored profilers relative to conventional current meter moorings include non-synopticity of the measurements and limited temporal resolution. The first is related to the time it takes for a profiler to traverse the water column (typically about 4 or 5 hours for a 5000 m deep ocean profile by the WHOI instrument). Finite battery size limits how many vertical profiles can be done during a given deployment.

In these regards, moored profilers and gliders share many of the same characteristics. Their active nature brings with it more potential failure modes than are typical for passive systems. Solving these "active" problems is an interesting challenge for the designers of moored profilers, as well as gliders and other AUVs. The ultimate success of these systems as oceanographic tools may rest on the quality of the solutions to this new problem set.

### 5.4 Autonomous Surface Vehicles

Autonomous surface vehicles (ASVs) have received less attention from developers than their underwater counterparts. However, a few projects are making significant advances. ASVs have several advantages compared to AUVs, including: simpler and cheaper energy supply, possibly using internal combustion engines and generators, easily providing ranges in excess of 1000 km; data communications and navigation are more straightforward; construction costs are lower; and transit speeds are higher. But ASVs are limited to making near-surface observations unless they carry automatic winches to emulate a standard shipboard hydrographic station. Current development projects include:

- Caravella – a multi-national EU Eureka programme led by the University of the Azores to develop a 7 m long, 2 m wide & 6 m high self righting autonomous surface craft with satellite data and control and a range in excess of 1300 km at 4 kt including an autonomous CTD winch. Commercial launch is expected in 2002. [Cara 99]
- SASS - from an UK consortium led by SeaSpeed Engineering Ltd. and the University of Southampton is a 5 m long semi-submersible design with a planned range of 600-1000 km at 12-15 kt and a 200 kg payload space. A 1/3 scale prototype has completed its trials and a commercial build is expected in 2001. There are no current plans to add an autonomous winch [Sass 99].

While recognising that ASVs may face similar legal issues to AUVs (see section 7), this class of platform does have considerable potential to contribute towards a sustainable observing system in coastal and continental shelf waters or in oceanic waters served by island bases.

## 5.5 Autonomous Underwater Vehicles

Propelled autonomous underwater vehicles (AUVs) have been under development by the military and civilian research community since the 1970's. Busby compiled a comprehensive review of progress up to 1987, [Busb 87] and Janes listed over 60 AUVs in the 1999 edition of Underwater Technology [Jane 99]. Over the last five years significant advances have been made; in particular, vehicles are now completing science missions funded through competitive programmes. AUVs have moved away from being test-beds for engineering evaluation, control and strategy theories; they are no longer curiosities.

Major projects underway in several countries are now at the stage of demonstrating autonomous missions of real scientific utility. But, perhaps naturally, at the present state of development, AUV missions are focused on process studies rather than sustained operational observations. Key examples include:

- A survey of coastal fronts in Hero Strait, British Columbia was completed in June 1996 by the MIT Odyssey II vehicle [Nadi 97] and the vehicles have been used in the harsh environment of the Labrador Sea in winter [MIT 99]. This team has made careful comparisons of the temperature and salinity measurements from Odyssey with those from a conventional CTD [Bale 94], showing that with careful sensor placement it was possible to achieve minimal contamination. Such experience is an essential prerequisite to acceptance of autonomous vehicle technology into an operational system.
- Although not an ocean science application, the 8.5 tonne Theseus AUV from International Submarine Engineering Research, Canada completed a 350 km round trip mission in April 1996 to lay a fibre-optic cable under sea ice in the Canadian Arctic [McFa 97]. This mission amply demonstrated the ability of AUVs to operate in environments otherwise only accessible by naval submarines
- Florida Atlantic University's Ocean Explorer vehicles have shown that it is possible to reduce the vehicle self-noise and vibration to such an extent that meaningful turbulence measurements can be made within the seasonal thermocline [Dhan 96].
- Southampton Oceanography Centre's Autosub-1 vehicle [Mill 98] completed a 53 hr, 263 km mission surveying the upper 500 m of the ocean off Bermuda in September 1998. The mission was part of the Autonomous Vehicle Validation Experiment which had an objective of demonstrating that an AUV could leave near-shore Bermuda, transit to the Hydrostation 'S' site and carry out physical, chemical and biological measurements and return to a near-shore location.

Following on from these achievements some of these groups have developed proposals to further demonstrate the utility of AUVs to ocean science. These include:

- ALTEX – the Atlantic Layer Tracking Experiment – a US NOPP-supported project using a vehicle developed from Odyssey to track the Atlantic water inflow into the Arctic Ocean. Novel features of the project include the regular deployment of satellite telemetry data capsules from the vehicle and a power supply based on a fuel cell [Alte 98].
- A trans-Atlantic transit by an AUV. Theseus is the only powered AUV with the energy capacity to cross the Atlantic. An eight-partner consortium led by the Autonomous Undersea Systems Institute proposed such a project in 1998. While there was little doubt about the capability of the vehicle to perform such a mission, the cost of the Lithium primary battery pack was too costly to be practical. Nevertheless, such a mission is technically achievable today.
- Under Ice Shelves. Little is known of the ocean circulation under ice shelves that occupy 40% of the Antarctic continental shelf or of the processes that take place. AUVs offer the opportunity to make interdisciplinary observations under warm water shelves in the south Pacific (e.g. Pine Island Bay Glacier); the cold water Filchner-Ronne Ice Shelf in the Weddell Sea as well as the Glaciers of north east Greenland (e.g. 79˚N Glacier). In addition to under ice shelf measurements, AUVs would be capable of traversing ice shelf – coastal polynya – sea ice regions measuring heat and salt flux and ice thickness. A programme proposal for such

observations during 2001-2005 is being prepared by the British Antarctic Survey and others [UIS 99].

AUVs have been proposed as a key component of multi-institution, multi-platform underwater surveillance and monitoring systems and initial feasibility trials have taken place involving moored and free-swimming components, communicating with each other and with scientists ashore using acoustic and radio communication [Schm 96]. AUVs shuttling between moored docking stations is one possible scenario for their early introduction as parts of a sustainable observing system. Much of the technology required for docking, recharging batteries, downloading data and communicating with shore has already been proven. The cost would be dominated by the capital depreciation of the AUV and the docking stations. Using realistic estimates of cost based on a large AUV amortised over 3 years; the cost would be of the order of $100 a km for a 1000 km transit between moorings. However, with a payload volume of ca. 1000 litres, such an AUV could carry an extensive instrument suite that reduced the cost ‘per variable’ to less than $10 a km. Capital costs of AUVs could reduce if economies of scale could be achieved in their manufacture, e.g. if the technology was to be adopted by the offshore oil and gas industry.

AUVs will become less and less dependent on support ships. They will also become able to leave and return to harbour autonomously. Limited demonstrations of such capabilities have already been made.

## 6. FUTURE DIRECTIONS

Some of the ideas on new platforms now at the stage of conceptual design or laboratory testing may survive long enough to become practically useful in 10-20 years. The same can be said for sensors, instrumentation and power sources. Candidate developments relevant to this paper include:

- Energy-efficient platforms based on bio-mimetics; replicating the swimming behaviour of marine animals;
- Very high energy density electrochemical cells; e.g. using hydrogen stored in carbon nanotubes and oxygen extracted from seawater; enabling very long duration deployments;
- Increasing trend towards using commercial mass-market sub-assemblies to minimise cost. For example, the fuel cell described above may have been developed for a laptop computer.
- Platforms specifically designed for sustained observations, bypassing the proving ground of process studies; driven by companies recognising the market potential of operational oceanography.
- Increasing use of adaptive sampling made possible through intercommunication between components of a system and between the components and shore laboratories.

The key issues of price and ease of deployment, use and data recover, reliability and appropriate accuracy of the data will also continue to test designers ingenuity.

## 7. LEGAL ISSUES

There are two main sets of legal issues surrounding the use of autonomous platforms at sea, the first is access, involving national and international public law, and the second is risk, primarily involving private law.

### 7.1 Access

There is no accepted framework in international maritime law for the operation of autonomous ocean measurement platforms. Indeed, there is no standard internationally accepted definition for such vehicles. A definition could include drifting profiling floats; it could certainly include gliders and ASVs as well as AUVs. Furthermore, only slow progress has been made over the last 38 years on a draft international convention on the far more mature technology of moored and drifting surface buoys, classed as ODAS (Ocean Data Acquisition Systems). The need was recognised back in 1961. It is possible that in any future redrafting of the convention autonomous platforms may be considered as a class of ODAS.

The legal aspects of access have been well reviewed (PRES 89) and an update has been commissioned by the SOC because of wider adoption of the UN Convention on the Law of the Sea since the original report. Current use of autonomous research platforms would come under the general heading of Marine Scientific Research, as detailed in Part XIII of the Convention [UN 83] and would seem to cover *inter alia* the transit and use of an AUV in a Coastal State's declared maritime zones, in particular its Territorial Sea. The articles detailing the rules governing access in relation to the Territorial Sea are set out in Part II of the Convention. However, operational use of AUVs might not be considered as marine scientific research; what effect this change from research to operation might have is a matter for debate. That debate might possibly take place under the auspices of the Advisory Body of Experts on the Law of the Sea (ABE-LOS) of the Intergovernmental Oceanographic Commission.

### 7.2 Risk

Some autonomous platforms have the potential to cause damage to third parties. A small number of users take out insurance to cover such risks as well as their own loss. The issues are no longer 'academic', as a collision between an AUV and another vessel has already resulted in a court case in Canada. As these platforms come to be used from a wider range of support vessels, including aircraft, then issues of liability may become more complex. Within the UK these issues have been recognised as needing a co-ordinated approach and the Society for Underwater Technology is to publish a code of practice for the safe and efficient operation of AUVs.

## 8. CONCLUSIONS

This paper has attempted to provide a realistic view of how new platforms currently being developed or in early use by the research community might contribute to a sustained observing system. As such, it is not 'future gazing', it is rooted in the present and supportive of a stepwise increase in capacity and technological complexity. By giving encouragement and broad direction to the ocean engineering community in academia, research institutes and companies the science community can help pull the technology into routine use.

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