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SeaCycler: A Moored Open-Ocean Profiling System for the Upper Ocean in Extended Self-Contained Deployments

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ABSTRACT

The upper ocean, including the biologically productive euphotic zone and the mixed layer, has great relevance for studies of physical, biogeochemical, and ecosystem processes and their interaction. Observing this layer with a continuous presence, sampling many of the relevant variables, and with sufficient vertical resolution, has remained a challenge. Here a system is presented that can be deployed on the top of deep-ocean moorings, with a drive mechanism at depths of 150–200 m, which mechanically winches a large sensor float and smaller communications float tethered above it to the surface and back down again, typically twice per day for periods up to 1 year. The sensor float can carry several sizeable sensors, and it has enough buoyancy to reach the near surface and for the communications float to pierce the surface even in the presence of strong currents. The system can survive mooring blowover to 1000-m depth. The battery-powered design is made possible by using a balanced energy-conserving principle. Reliability is enhanced with a drive assembly that employs a single rotating part that has no slip rings or rotating seals. The profiling bodies can break the surface to sample the near-surface layer and to establish satellite communication for data relay or reception of new commands. An inductive pass-through mode allows communication with other mooring components throughout the water column beneath the system. A number of successful demonstration deployments have been completed.

1. Introduction

The upper layer of the ocean, from the surface to a depth of approximately 100–150 m, is a very dynamic component of the oceanic water column. It contains important physical, biogeochemical, and biological processes, which need to be observed with good temporal and vertical resolution while maintaining a long presence in order to unravel their interconnection or even just to gain information about the short-term variability, climate-driven responses, or long-term evolutions in this layer. For a wide variety of quantities it is necessary to know the vertical structure (gradients or maximum/minimum layers) and/or the vertical integral or the vertical movement of layers. Prominent examples are the mixed-layer structure (density gradients, heat distribution), phytoplankton (which usually have a

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subsurface maximum), nutrients, or pCO_2 (whose vertical distribution is needed for carbon budgets and fluxes). For these reasons, time series collected with fixed-point sensors often deliver insufficient information. Some variables can now be observed with small and power-efficient sensors, such that they can be mounted on underwater gliders or profiling floats, to obtain vertical profile information. Other variables require larger or more power-hungry sensors, for example, imaging flow-through systems like Laser Optical Plankton Counters (LOPCs) and wet chemical sensors for carbon variables or nutrients. Also, time series may be needed in locations where gliders cannot hold station well enough (strong current systems or in eddy fields). This requires a profiling technology that can be mounted on moorings to transport sensors through the surface layer.

Moorings with a surface buoy are difficult to use for profiling systems since the mooring wire can move violently under the action of surface waves. The damage potential of the surface or near surface is also well recognized, and thus minimizing the time spent there is a common feature shared by many profiling systems operating on subsurface moorings. Various profiling designs have successfully employed variable buoyancy to drive a near-neutrally buoyant element up and down a taut mooring wire (Van Leer et al. 1974; Eriksen et al. 1982; Provost and du Chauffaut 1996; Waldmann 1999; Budéus 2009). The near-neutral buoyancy requirement, which minimizes energy input, tends to restrict the instrumentation suite that may be carried, and, since the force developed by buoyancy change is quite small, ambient currents can negatively affect the system's ability to move vertically. The concept of operating on a taut wire has been dramatically extended by Doherty et al. (1999) using a motor/pinch wheel system running on a taut-wire subsurface mooring cable. This system has been deployed operationally on wide-ranging oceanographic studies (Morrison et al. 2000; Krishfield et al. 2008; Nikoloupoulos et al. 2009; Toole et al. 2011). Like the profilers that rely on buoyancy change, the driving force is low so ambient conditions can have an influence on performance and the near-neutral buoyancy requirement can impose instrument suite/power capacity challenges. But, depending on mooring configuration, ambient conditions, and water depth, these systems can operate from near the bottom and approach the near surface. Because all these designs operate on subsurface moorings, there is the implication that, without some parallel structure or operating system, data need to be stored internally.

The current approach discussed in this paper also employs a subsurface mooring but one that ends approximately 150 m below the surface and incorporates a winchlike system at this depth. This arrangement is more tolerant of extreme weather conditions since it can stay well below the surface when waves and wind are too severe and is less likely to be damaged by ships or vandalism. A winched system also avoids the "reef effect," that is, marine life that gathers around and attaches to near-surface moorings, and thus can observe a more undisturbed marine ecosystem since sensors parked at a depth of 150 m are less affected by biofouling.

But there are a number of challenges associated with a moored underwater winched system that need to be overcome. A main factor is the energy efficiency, assuming the entire mooring is self-contained and thus battery powered. Underwater winch systems have been developed, however, that can operate from the bottom or from a midwater platform. An innovative profiler that carries the winching component on board a buoyant profiling element has been developed (Barnard et al. 2010) and has been operationally deployed. This system is designed to pierce the surface to permit data transmission. But because the magnitude of the force, exerted by buoyancy, that is required to raise the system to the surface is highly dependent on the ambient current, the size of the profiling package, and operational depth, a potentially restrictive balance exists between the power available and the duration and number of applications of that force. Just the same, it has been demonstrated that many profiles are possible in weeklong deployments in shallow water (Sullivan et al. 2010; Babin et al. 2005). A compact variant of the onboard winch system has been used to obtain temperature data from the upper water layer beneath Arctic ice by Pickart (2007).

Plain winching requires significant energy to pull down a body that has enough buoyancy to overcome the blowover due to horizontal drag in typical ocean surface currents. Drag is especially serious when large and heavy sensors are to be deployed on the profiling body. This difficulty has been addressed by Fowler et al. (1997). Here wave energy is used to drive a buoyant profiling element down a mooring line, which is then permitted to rise under its own buoyancy. The energy available permits the use of a substantial sensor package and makes the system insensitive to ambient current but also makes it virtually impossible to stop the profiling element in midprofile if a sensor might require it. Collected data are stored internally and transmitted inductively to the surface where a two-way communication system can transmit the data to shore or receive and relay commands from shore to the profiling package. The downside to this approach is that keeping a permanent surface expression in place and functioning properly in all weather conditions is difficult. This drive system has been later duplicated by others (Rainville and Pinkel 2001; Pinkel et al. 2011).

A second challenge is the operation of rotating mechanical parts and electric motors underwater over long durations. Typically, this requires rotating seals and underwater electrical slip rings, which increase the risk of failure when deployed for time periods in the order of 1 year. A third complication is the fact that subsurface moorings in the deep ocean (5000-m depth) may be blown over by strong current events such as eddies. At high latitudes these currents can be deep reaching and may cause the components that are normally at a depth of 150 m to be pushed down to depths of 700–1000 m. Thus the entire winch assembly needs to be pressure resistant to such depths. Finally, to establish communication to shore, it is necessary to break the surface and remain there while transmitting data or receiving commands. This is hazardous and challenging because a large float with ample buoyancy will be subject to snap loading in the wave field, while a small float may be continually swamped by waves or may not even reach the surface in the presence of currents.

This paper presents an approach that tries to respond to all the challenges resulting from the above requirements and represents considerable collaboration between engineering and science teams over the course of 6 years to produce the system now called SeaCycler. Several ideas and principles are derived from an earlier system called ICYCLER (Fowler et al. 2004), which was developed for making daily measurements under ice for a period of a year. The solution and implementation presented here combine the following features:

- an energy-conserving principle, to increase power efficiency by an order of magnitude over conventional systems (Fowler 2002);
- a totally enclosed drive system (no rotating seals or slip rings) to increase reliability;
- a large instrument payload (60 kg in air) permitting flexible scientific studies;
- a ‘‘Sensor Float’’ buoyancy of 110 kg to allow surfacing in strong currents;
- a pressure rating of 1000 m, to allow deployment on deep open-ocean moorings;
- extra cable storage (total of 373-m net) to compensate for blowover in currents;
- a ‘‘parking depth’’ of 150 m, to avoid storm waves, reef effect, and vandalism and reduce biofouling;
- ambient wave sensing capability to avoid surfacing when conditions are too severe;
- a separate ‘‘Communication Float’’ to establish shore telemetry even when the Sensor Float remains below the surface;
- remote retasking;
- simple straight-through cable routing, anchor to surface, allowing inductive modem coupling to deeper-water instrumentation;
- an endurance of approximately two or four 150-m profiles per day in a yearlong deployment, for alkaline or lithium batteries, respectively;
- 550-kg buoyancy to help maintain a taut mooring; and
- an ability to surface the Sensor Float for maintenance without recovering the mooring.

This system has been deployed for engineering and demonstration purposes on multiple occasions and during the most recent deployment carried out 644 round-trip profiles from a depth of 150 m using an alkaline battery pack.

2. Technical implementation

a. Mechanical design

As shown in Fig. 1, the SeaCycler system comprises three floats connected by electromechanical cable. At the top is a Communication Float (short ‘‘Comm Float,’’ 5-kg net buoyancy), followed by a Sensor Float (105-kg net buoyancy including an extensive sensor suite). Both floats travel in tandem through the water column under the action of the lower Mechanism Float (440-kg buoyancy), which also provides flotation for the mooring that connects it to the ocean bottom. The Mechanism Float contains a winch drum/motor assembly, shown in the detail in Fig. 1, which is not only highly efficient but also mechanically simple. The smaller diameter section of the drum stores 6-mm-diameter 3×19 steel galvanized plastic-jacketed mooring wire (1800-kg breaking strength), and the larger-diameter section carries a near-neutrally buoyant plastic-jacketed, spectra strength member, three conductor, profiling cable leading to the Sensor Float. Rotation of the double drum produces differential movement of the two cables in the ratio of the drum diameters, here set at 5:1. Since the cables are wound in opposite directions, drum rotation causes the profiling floats and the Mechanism Float to move vertically in opposite directions. Because the various buoyancies are carefully designed to produce tensions in the cables that are in the inverse ratio, that is, 1:5, the drum is in static balance and can therefore be rotated with very little torque and resultant power. Put another way, rotation of the drum changes the potential energy of the Sensor and Comm Floats but this is offset by an equal and opposite change in potential energy of the Mechanism Float. This energy-conserving principle has been patented. The balance of the system is critical for energy conservation, but minor variations are

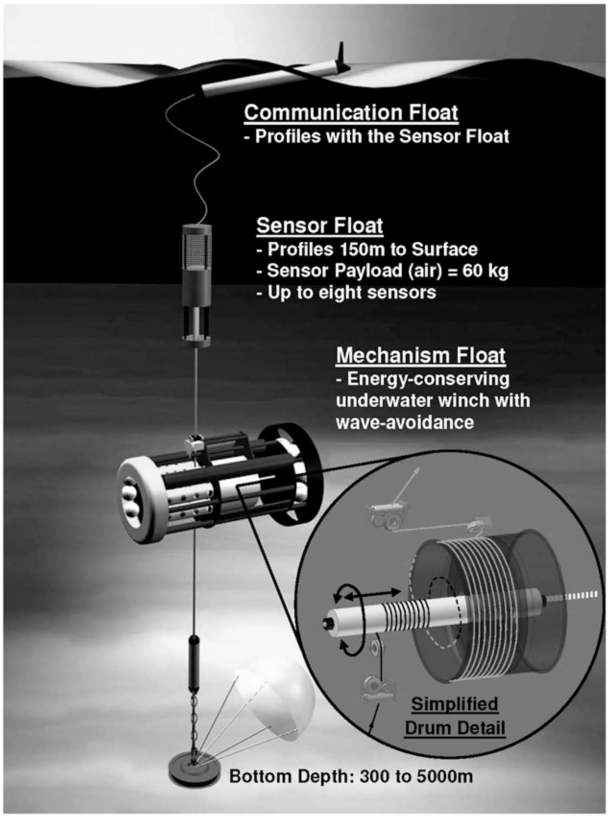

FIG. 1. Schematic showing the overall design and configuration of the SeaCycler system. The Mechanism Float (MF) is typically parked at 165-m depth with the Sensor Float (SF) pulled in close. The Communication Float (CF) is connected via 23 m of fixed-length cable. During profiling, the MF moves downward while the SF ascends, in a 5:1 ratio. If there are no water currents and associated blowover of either the mooring with the MF and/or of the SF, the MF winches itself down to 195 m while the SF reaches the surface. To allow for mooring blowover, the total cable stored allows for spooling out 466 m of cable for the SF, and this requires 93 m of cable capacity for the MF. At maximum payout the MF may thus be at a depth of 258 m, resulting in a ''net'' SF cable length (relative to 150 m) of 373 m, or 223 m of spare profiling capacity allowing for mooring blowover. Dimensions of the floats are as follows: for MF, length is 4.0 m, maximum diameter is 1.8 m, air weight is 1850 kg, and buoyancy is 440 kg; for SF, length is 2.5 m, maximum diameter is 0.6 m, air weight is 230 kg, and buoyancy is 105 kg; and for CF, length is 1.4 m, maximum diameter is 0.1 m, air weight is 18 kg, and buoyancy is 0.2 kg. Arrows on the left in the drum detail indicate bidirectional rotation and the associated translation forced by the axially mounted lead screw on the right.

tolerable. The cables, which are alternately spooled on and off the drum, can contribute to an imbalance but are chosen, particularly the profiling cable, to have minimum in-water weight. As a result, only minor variations are detected in the drive motor power consumption throughout a profile.

Several challenges were met in the design and integration of the winch drum's drive motor assembly.

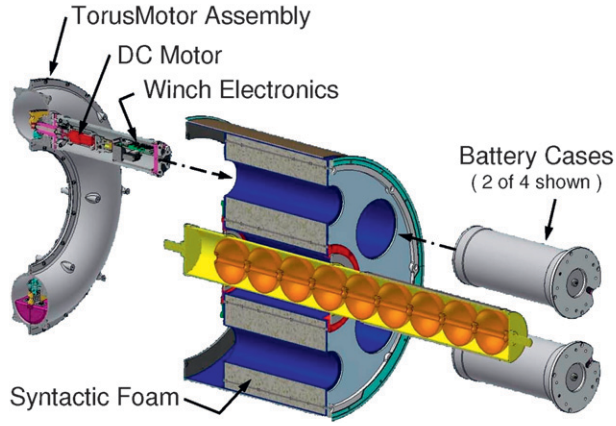

FIG. 2. Cutaway view of the neutrally buoyant winch drum assembly showing how the torus motor, winch electronics, and battery packs are mounted.

Primary among these was the need to overcome the projected cyclical unbalancing torques caused by wave forcing when profiling elements approach the surface. These forces, in combination with the large torque arm offered by the drum, forced a new approach to underwater motor design. Instead of mounting the drive motor on the centerline, where immense output torque would be required, it was connected near the outside diameter of the drum to a large internal gear. To resist anticipated high ambient pressures, this assembly was housed in a torus-shaped pressure case (1.1-m outer diameter) (Fig. 2). This geometry offers a substantial diameter to create torque while keeping the wall thickness of the pressure case thin (11 mm) to generate a lightweight assembly. The drive mechanism inside the torus consists of the large internal gear integral with a substantial steel ring that is supported on five bearings mounted on the torus enclosure wall. These bearings disconnect the ring, and gear, rotationally, from the torus. The ring is eccentrically weighted to create a pendulum. A small dc motor (40 mm $\times$ 70 mm, 150 W) mounted on the torus is engaged with the internal gear on the ring so that when the motor rotates it causes the torus, with attached winch drum, to rotate around the centerline of the pendulum ring. Since the batteries and control electronics are also located inside the drum and thus rotate with the entire assembly including the motor, no slip rings are required to transmit the power nor is there a need for any rotary seals. Significantly, gravity, working on the pendulum ring, acts as an elastic vertical reference, or ''foot on the ground'' from which to create torque. When the torus rotates under no-load conditions the pendulum ring remains comparatively stationary, but under load the pendulum rotates to create torque so that the whole assembly is rotationally compliant—an absolutely critical feature for a structure that operates in the wave zone. Notably, all the gearing and relative motion required to produce drum rotation occur in air, within the torus itself, enhancing efficiency.

At low profiling speeds the major part of the energy required to move the Sensor and Comm Floats in the water column is produced by the frictional forces within the mechanism itself. To limit frictional losses, the neutrally buoyant drum is driven horizontally by a fixed, axial lead screw under stationary fairleads while cable, laid in a single wrap, is pulled in or paid out (Fig. 1). This eliminates the need for power-consuming and mechanically complex spooling mechanisms. Since friction reduction is so critical for power conservation, great care was taken with the design of all rotating elements. All fairleads and the main winch shaft are supported on ball bearings that are enclosed in oil-filled, pressure-compensated housings that isolate them from seawater and have proven to be highly efficient. Drum translation is supported on simple low-friction bushings that consume little power at the extremely low translation speeds involved.

At first glance the winch drum may seem ungainly but its large size actually serves multiple purposes. The larger section is 1.15 m in diameter and 1 m long and is capable of storing 466 m of profiling cable in a single layer. It is also large enough to house the electronics and all the batteries (576 alkaline D-cells in four packs) needed to power drum rotation. Although the mechanism is in static balance due to the buoyancies and cable wrapping, external forces such as hydrodynamic wave loading on the profiling floats as they approach the surface can impose significant torsional forces on the drum. These forces are resisted by the motor assembly with the torus-shaped pressure housing having almost the same major diameter as the larger section of the drum itself. The motor is thus capable of substantial output torque. Finally, sufficient space is available to include enough syntactic foam to render the whole drum assembly neutrally buoyant, which is essential to maintain level trim as the drum translates. The motor assembly, winch batteries, and control electronics all rotate with the drum providing a seamless cable routing right through the entire SeaCycler assembly from the ocean floor to the surface. (Fig. 1, drum detail)

b. *Power budgets*

It is essential that adequate float buoyancy be provided to ensure that oceanographic sensors and communication elements reach the surface when high water currents are encountered. Further, both the ascent and descent must be accomplished under controlled conditions to ensure proper instrument function. For the operational parameters defined in this project where the parking depth is set at 150 m, and with a substantial sensor suite that can add to float size, models predict that a combined buoyancy on the Sensor Float and Comm Float of 110 kg is required to lift the profiling elements to the surface when near-surface currents reach as high as $0.8\,\mathrm{m\,s^{-1}}$ (assuming no lower mooring knockover). Of course, this is an oversimplification. The mooring is affected by currents throughout the entire water column, and when the system is moored in deeper water additional buoyancy will be required beneath the assembly to keep the mechanism float within the profiling range.

Actual field experience indicates that the SeaCycler operates with an average overall power consumption of 60.7 W, and this includes power for mechanism control and monitoring electronics. Comparisons with a ‘‘conventional’’ winch system, where the profiling buoyancy must be pulled down by brute force but is allowed to ‘‘free ascend’’ under control to the surface, are difficult because of assumptions that must be made about efficiencies and low load power requirements. Nonetheless, calculations show that the SeaCycler should be on the order of 10–12 times more efficient. For equal onboard power that means 10–12 times more profiles.

The Mechanism Float carries 600 A h of energy at 24 V in alkaline batteries for profiling and to power the electronics. In the current configuration, power is adequate to complete 650 profiles: 150-m round-trip profiles or 195-km profiler travel. The Sensor Float carries a 14-V lithium battery pack with 320 A h of energy that powers the main system control electronics, all the sensors [at present: conductivity–temperature–depth (CTD) and dissolved oxygen] plus the Comm Float electronics and transceivers. Replacing the Mechanism Float batteries with lithium cells would permit more than doubling the number of profiles, or alternatively, completing up to two profiles per day for a year in areas that experience much higher water currents that will need more cable payout to reach the surface. To do this would also require doubling the Sensor Float power since instruments will be on for longer periods of time. Within the 0.6-m circular envelope of the Sensor Float, with two 0.6-m bays, there is sufficient space and, by removing the current 20 kg of lead ballast needed to achieve balance, adequate buoyancy to accommodate this change as well as increase sensor payload to eight instruments.

c. *Electronic interfacing, communication*

During profiling, main functional control, instrument management, winch control, and communication reside on the Sensor Float along with CompactFlash drive data storage. During data telemetry to shore, the Comm

Float becomes the master and the Sensor Float responds to its commands either locally from the Comm Float or remotely from shore via the Comm Float. Ancillary and backup CompactFlash drive data storage is sited on both the Mechanism and Comm Floats. Intercomponent communication among the three floats is accomplished through a direct, full-duplex serial link using three conductors on the interconnecting electromechanical cables.

The Sensor Float manages the mission planning as well as data file transfers between all floats. Functional control includes parameters such as the profiling interval, profiling speed, and the minimum depth to which the Sensor Float is profiled, or ''stop depth,'' on the way up. On the way down, stops can be ordered to accommodate sensor equilibration. Depth control is effected by the pressure signal from the onboard CTD data. All of these parameters can be modified by the shore operator during any of the regular telemetry sessions. Provisions have been made for the Sensor Float to ''wake up'' and/or reset any of the SeaCycler subsystems as required. The profiling sequence is governed entirely by Sensor Float commands, which can be dispersed to all instruments and subsystems. In addition, an acoustic modem is included on the Sensor Float to provide control and status during periods where the Comm Float is submerged. Currently, it is configured to act solely as a ''Full System Reset Mechanism'' to bring the Sensor Float to the surface in the case of a catastrophic electronic communication failure. Provisions have been made, though, for auxiliary instrument data transfer, system control, and status reporting.

The Mechanism Float contains its own control system that responds to both simple and complex commands from the Sensor Float. Simple commands include functions such as turning the brake on or off, while more complicated commands can effect a complete surfacing profile based solely on the Mechanism Float's internally established criteria. The Mechanism Float electronics incorporates sensors that allow it to control and monitor all of its internal functions. Operating parameters, such as winch drum speed, maximum allowable torque, and motor current are accessed locally but can be overridden by commands directly from the Sensor Float or from the shore operator via the Comm Float to the Sensor Float.

Two-way communication over the Internet between a shore computer and the SeaCycler is accomplished via an Iridium Communications, Inc., transceiver located on the Comm Float, which also includes a GPS engine. Local communication with the surfaced Comm Float, that is, to a ship in the vicinity, can also be accomplished via a FreeWave Technologies, Inc., transceiver. The Comm Float activates a ''sniffer session'' at the beginning of each telemetry session. During this ''sniffer'' phase, a user in the area can download data or gain control of the mooring via FreeWave. If there is no FreeWave signal that is sensed to ''talk'' to the Comm Float, it will follow up with an Iridium session attempt to shore. If the FreeWave attempt is successful, the Iridium session is abandoned for that profile. The Comm Float is a completely self-contained communications subsystem. All of the Iridium, FreeWave, and GPS communications are controlled by the Comm Float electronics. Files destined for shore are typically transferred from the Sensor Float to the Comm Float during the surfacing phase of the profile, where they are stored in the Comm Float's internal file system. The Comm Float data storage provides full redundancy for all files throughout a deployment. A command from the Sensor Float then relinquishes control to the Comm Float where it will establish the connection, transfer files, and receive new commands from shore. All new files are automatically transferred to shore, but any of the archived files may be retransmitted at the request of the shore operator. Time updates from the GPS and commands from the shore operator are transferred to the Sensor Float to be later dispersed throughout the system.

The uninterrupted nature of the cable routing from the Comm Float through the Sensor Float through the Mechanism Float winch drum to the mooring line below means that direct communication is possible from shore to the ocean bottom. Currently, communication with instrumentation located on the mooring line beneath the Mechanism Float has been accomplished using an inductive modem.

Iridium/GPS emergency recovery beacons are located on both the Sensor Float and the Mechanism Float. With a planned stand-alone power addition on the Comm Float, it will be able to act as an emergency recovery beacon as well.

d. Performance aspects

There are four separate functional features that affect the ability of a system to approach the surface, pierce it to send and receive data, and then submerge. The first is the need for extra profiling cable beyond the absolute depth of the system. SeaCycler carries 466 m of profiling cable that, when it is all deployed, results in a net upward movement of 373 m by the Sensor Float to reach the surface. This in effect accommodates a 223-m mooring knockover. It must be noted that the Sensor Float ''parks'' itself approximately 3 m above the Mechanism Float, and as such imparts a small profiling gap (or blind spot) between the top of the Mechanism Float and the Sensor Float. The part of the mooring between the

FIG. 3. Communication Float in its operating position at the surface. Tank and field studies have shown remarkable stability with waves ranging from capillary to wind waves and swell, always keeping the antennas out of the water.

parking depth and lowest possible depth of the Mechanism Float is also a section where the mooring can carry no sensors and where the Sensor Float does not reach. In the current configuration this depth range is 93 m long and would be a blind spot unless sensors desired for this interval are mounted on the Mechanism Float.

The second is the effect that varying wave forces have on any structure or body at or near the surface. These forces can have a very negative effect on the longevity of systems that are ‘‘unyielding’’ and have the potential of imposing exaggerated snap-loads on fixed cable structures. The design of the SeaCycler motor, however, has built-in and automatic compliance that radically reduces potential stress on the system and can, under certain circumstances even ‘‘give up’’ cable if forces become excessive.

The third aspect, piercing the surface, is accomplished by SeaCycler's Comm Float. This relatively small component, about 1.5 m long, floats near vertical when submerged at the top of a 23-m-long double-armored steel cable that is rendered neutrally buoyant by the addition of discrete syntactic foam buoyancy elements. When it pierces the surface it flips to an almost level attitude because of off-center ballasting. In this state it projects a three-element antenna above the surface; see Fig. 3. The combination of neutrally buoyant cable lead-in, ballast placement, and the very large water-plane area created by its near-horizontal attitude dramatically enhances stability, allowing the Comm Float to transmit and receive messages in significant waves. Data have been successfully transferred in 4.1-m waves.

The fourth function, submerging in heavy weather, however, represented a significant challenge in early sea trials. It was found that when the weather got rough, in seas of over 4 m, the Comm Float could sometimes be left on the surface for extended periods after an Iridium communication session. Wave drag force on the profiling elements exceeded maximum motor torque so that they could not be hauled down. This was eventually overcome with a stratagem that took advantage of SeaCyler's unique motor/energy balance principle. As noted, the three buoyancies that compose the assembly are organized to maintain balance. When this balance is upset, for instance, when transient wave forces are encountered, the system attempts to restore this balance automatically and autonomously in a very useful way. In the normal stopped position, for example, when on the surface and transmitting, the system is locked with an internal brake. We found, however, that if the brake was disengaged, the system's predisposition to maintain balance combined with the Mechanism Float's large buoyancy took over and the profiling elements were ratcheted down by passing waves as the Mechanism Float, momentarily out of balance with applied cable tensions, rose in the water column to restore balance. This technique has become standard procedure, and the system has been programmed to remove the brake for 2 min after each surfacing session. Even in relatively calm, 1-m seas, the profiling elements are often hauled down to a depth of 10 m. But as wave height increases, the ratcheting effect becomes more intense so that, instead of expending considerable energy to submerge, the waves provide a ‘‘free ride’’ down to 20 m or more in larger waves. This is particularly advantageous in helping the SeaCycler escape from rough sea conditions. The more severe the threat is from waves, the deeper the waves drive the profiling floats down away from the challenging wave environment, thus protecting the system from potential damage.

It should be noted that surfacing the Sensor Float on command allows it to be accessed, for example, to service or replace sensors, while keeping the remaining mooring including the Mechanism Float in place and operational. Figure 4 shows the Comm and Sensor Floats on the surface.

3. Demonstration

Between March 2010 and May 2011, seven deployments have been accomplished: three in shallow local waters, two in ~150-m water depth 32 km off Halifax, and two at the edge of the Scotian shelf in ~1100-m depth 250 km offshore. These field tests were combined with countless laboratory and jetty tests. The five inshore and near-shore test deployments were of short duration, typically 3 days, with the offshore deployments lasting 74 and 41 days, respectively. As would be expected for a development this ambitious, early deployments identified minor shortcomings. These were corrected with additional innovations or additions to

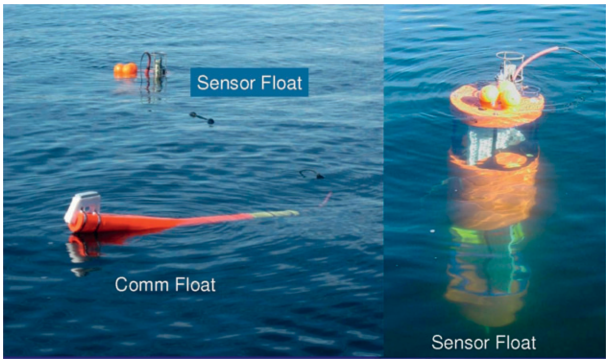

FIG. 4. Photographs showing the Comm and Sensor Floats on the surface during the middle of deployment. The CTD sensor is out of the water, and the remainder of the Sensor Float remained submerged.

culminate in the last deployment, which was highly successful both from a performance perspective but also from the standpoint of operational development. Chief among these was the implementation and refinement of the autonomous wave-driven submergence. Over the duration of the last deployment the power savings realized through this technique represented twenty-six 300-m round-trip profiles, or 4% of the 644 profiles completed, expending no rotational power at all.

In the local waters tests, the Mechanism Float was towed to the deployment site and the other two floating components were streamed aft before deploying mooring line and dropping the anchor. The offshore deployments were accomplished using Coast Guard vessels of various types, but in all cases operations were conducted from the foredeck or waist rather than from the stern. This cumbersome method was only made possible with the aid of a secondary small boat to tow the floating components away from the ship and keep them organized in a straight line as the ship moved away ''crabwise,'' deploying mooring line, before dropping the anchor. Operational plans call for working from an oceanographic vessel where components can be deployed sequentially, mooring top first and anchor last, from the stern, which is our normal practice. It goes without saying that, whatever platform is used to deploy the large Mechanism Float, care and proper rigging are essential to combat its potentially large inertial forces. Figure 5 shows all three float bodies on a Coast Guard vessel prior to deployment.

A significant portion of the testing process was concerned with the evaluation of communication capability. Initial satellite communication difficulties were identified as a possible compatibility issue with the TCP/IP stack in Microsoft Corporation Windows XP and the shoreside server software. After migrating to Windows 7 (which has a more current TCP/IP stack design), the

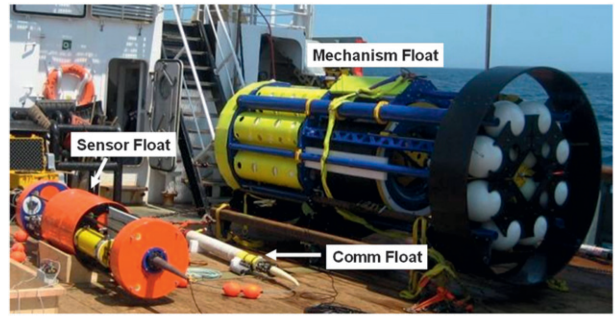

FIG. 5. View of all three float bodies on a Coast Guard vessel prior to deployment. The Sensor Float is seen to have ample spare capacity for additional sensors, batteries, or electronics.

problem disappeared. Further investigation is ongoing with Microsoft and Iridium to fully understand the matter, but for now it is not viewed as a serious issue. This malfunction resulted in many dropped calls but, for these, data were recovered during shore-requested retransmission.

The system's operating characteristics such as profile schedule, profile stop depth, and torus-motor pendulum angle, which defines available motor torque output, were varied from shore. This was done primarily to test functionality but at the beginning of the deployment we were actually learning how to best run the system and garner some idea of what the operational limits might be. In fact, the team is still learning about how the system responds to its environment and what is the best way to set parameters to maximize operational efficiency. At the beginning of the deployment, maximum motor current was varied to assess its impact on SeaCycler's ability to approach the surface in varying wind and wave conditions, and this is easily seen in the early part of the oxygen record of Fig. 7 as stops occurred as deep as 30 m. Typically, we start to ''see'' or feel the effects of the surface as deep as 45 m. Once we had gained some information on performance, ''normal'' Sensor Float stop depth was set at 5 m. But on 82 occasions it was brought to within 1 m of the surface, and on 23 profiles the CTD water inlet was surfaced into air. Indeed, on command, the top end of the Sensor Float itself was actually brought above the surface. The graph in Fig. 6 shows, with respect to wave height, the occasions when the system did not achieve its instructed stop depth. After the initial experimentation with surface approach, only eight profiles failed to reach desired depth, which represents only about 1.3% of the total number of profiles. Even though the Sensor Float did not reach requested depth, the 23 m of cable above it meant that the Comm Float was at least able to make an attempt at communicating with the satellite with routine success. The dotted trend line shows the anticipated upper limit of profiles with respect to wave height and confirms the

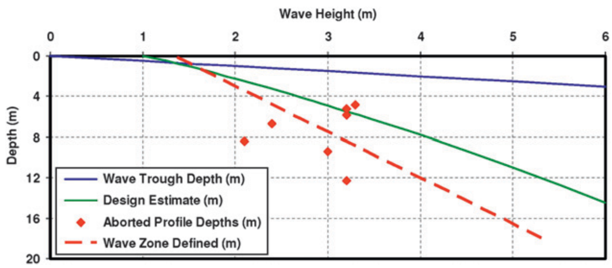

FIG. 6. Profiles that did not reach the requested stop depth are shown for various wave heights. These represent a very small number relative to the number of profiles completed. Even though these profiles stopped early, there was still an excellent chance that the Comm Float would pierce the surface to relay data due to the 23-m cable separation between the Comm Float and the Sensor Float where these depth measurements were actually made.

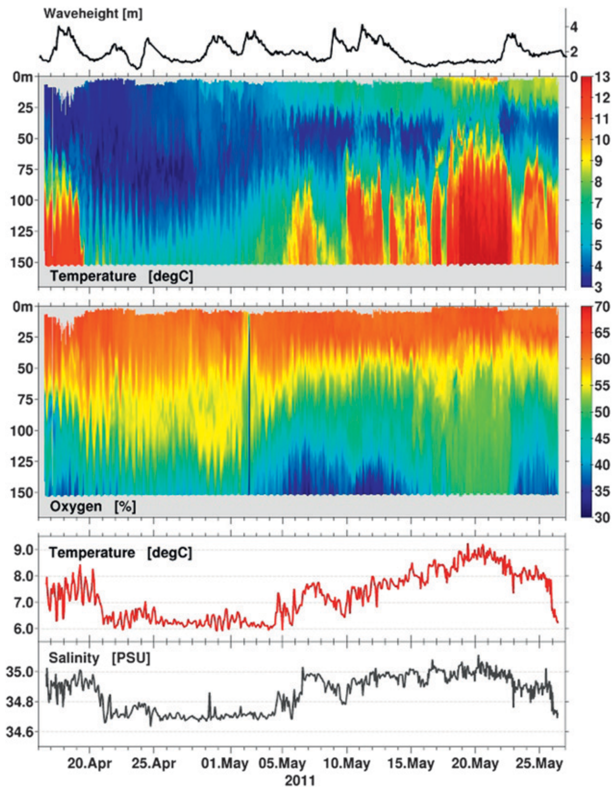

FIG. 7. Time series display of the real-time recovered data for all 644 profiles from the deployment in 1100-m water depth in the open ocean off Halifax (April–May 2011), together with wave conditions from a near-by National Data Buoy Center buoy. The lowest two panels show data that were retrieved from a Sea-Bird Electronics, Inc., MicroCAT farther down in the mooring, using the inductive communication capability made possible by the single connected cable routing from the Comm Float to the mooring wire below SeaCycler.

original design study results. One failed profile is not shown on the graph since profiling was terminated after only 7 m of travel because of an unexplained motor shaft encoder error.

On the other end of the spectrum, successful two-way communication was demonstrated in wave heights over 4 m. The instrumentation carried on all the deployments worked flawlessly with 100% data recovery rate. There were occasions when data file transmissions were terminated prematurely, a few for no apparent reason, but invariably these were recovered on command in a later transmission. Some instrument data are shown in Fig. 7 for the 644 profiles of the most recent deployment.

Power consumption was found to be very close to original estimates with an average winch power expenditure of 60.7 W while profiling or 15.1 W h per 300-m round-trip profile, which includes additional power demands of surfacing and submerging. The total number of profiles completed is commensurate with the original design objective. Although project planning called for only 365 profiles, supplementary battery power was provided to deploy and recover an additional amount of cable to surface the profiling floats in higher water currents. The site chosen for the deployment has been extensively studied over past years, and, although currents were judged to be low, it was anticipated that occasional higher-current events could be expected. In the event, water currents at the site proved to be consistently very low so that only 2–4 m of additional cable was required to reach the surface. The extra energy conserved by reduced profiling distance was used to complete 644 m × 300 m round-trip profiles instead.

4. Outlook and future applications

At the time of writing, SeaCyler is in the water for a test deployment as part of a National Science Foundation (NSF)-funded Ocean Observatories Initiative (OOI) effort. For this it carries a pCO_2 sensor and an acoustic current meter in addition to the CTD and dissolved oxygen sensor. The plan is to migrate the technology from the Bedford Institute of Oceanography (BIO) Ocean Physics group to the commercial manufacturer/vendor, Rolls-Royce Canada Limited–Naval Marine. We feel confident that the SeaCycler principle provides a very robust and energy-efficient method of obtaining profiling data in the upper ocean. Sensors that lend themselves to integration range from CTD and current meters, fluorometers and backscatter sensors, and incoming radiation sensors to acoustic zooplankton sonars, wet chemical systems for carbon and nutrient measurements, and LOPC systems. It is possible to move to steel wire for all cables, providing more fishbite resistance. In this case additional electronic cable communication complexity will be necessary to permit operation using a single conductor rather than the multiconductor system currently employed. The additional weight of the wire spooled out can be compensated by tapered drums to keep the system balanced. Experience needs to be gathered with procedures and possibly hardware for safe deployment and recovery of the large and heavy SeaCycler system. Recovery may be simplified by first detaching SeaCycler from the subsurface mooring with an acoustic release—this will be explored during the OOI test deployment.

An additional modification for future applications may be possible by providing power to the mechanism float from below (in case a seafloor cable is available to provide power). Also, this version of SeaCycler is a most ambitious design, allowing for blowover to 1000-m depth. It may be possible to build modified versions for coastal applications that only need to operate to depths of 200 m.

Overall, SeaCycler is an underwater moored winch system that is designed for applications in demanding situations, that is highly flexible and robust, and that has proven its readiness for extended field deployments in research applications.

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