An inductive charging and real-time communications system for profiling moorings

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ABSTRACT

We describe a system for providing power and communications to moored profiling vehicles. A McLane Moored Profiler (MP) was equipped with a rechargeable battery pack and an inductive charging system to allow it to move periodically to a charging dock at the top of the subsurface mooring. Power was provided from a large bank of alkaline batteries housed in two 0.95m steel spheres. Data were transferred inductively from the profiler to a mooring controller, and from there back to shore via radio and Iridium satellite modems housed in a small surface communications float on an “L” tether. An acoustic modem provided backup communications to a nearby ship in the event of loss or damage to the surface float. The system was tested in a 180-m-deep fjord (Puget Sound, WA) and at station ALOHA, a 4748-m deep open-ocean location north of Hawaii. Basic functionality of the system was demonstrated, with the profiler repeatedly recharging at about 300W (with an overall efficiency of about 70%). Data were relayed back to shore via Iridium, and to a nearby ship via the radio and acoustic modems. The system profiled flawlessly for the entire 6-week test in Puget Sound, but charging at the deep site stopped after only 9 days in the deep-ocean deployment owing to damage to the charging station, possibly by surface wave action.

1. Introduction

The ocean occupies a dauntingly wide spectral domain, in four dimensions of broad extent. It is well known that ocean processes at all scales affect each other, calling for accurate parameterizations of the small-scale ones. For example, diapycnal mixing takes place on centimeter scales, and is primarily driven by internal waves (hourly to daily time scales), but profoundly affects processes on all scales including the general circulation (megameter scales, Simmons et al. 2004; Ferrari and Wunsch 2009; Waterhouse et al. 2014; Melet et al. 2013). These cross-scale dynamic linkages, intrinsic nonlinearity, and the ocean’s sheer size necessitate observations of temporal scales of seconds to decades, while at the same time
observing the entire water column with high (\(\sim 10 \text{ cm}\)) vertical resolution. This must be done at as many horizontal locations as possible.

Profiling vehicles such as the McLane Moored Profiler (Morrison et al. 2001) offer a huge improvement over fixed-depth sensors in their ability to provide time series of vertical profiles. However, battery life currently limits their endurance to a total of \(O(10^6)\) vertical m. For a year-long deployment in deep water, this necessitates daily profiles, missing a significant fraction of the kinetic energy in the ocean (Ferrari and Wunsch 2009; Alford et al. 2012) and aliasing internal waves and tides onto the resolved frequencies. Or, to better resolve these motions with (say) hourly profiles, the overall mission length is only 46 days, missing seasonal and longer timescales and limiting spectral resolution. These issues can be partly resolved by adding more profiling vehicles which each sample only part of the water column (Alford 2010), but at greater expense and raising issues with intercalibration. Floats and gliders, in addition to not being able to station keep as well as moorings, generally profile more slowly (10 cm/s as opposed to 25 cm/s), reducing the vertical aperture that can be studied without undue aliasing internal wave motions (Johnston et al. 2013).

We report here on an attempt to improve the system’s endurance by developing an inductive charging system (Figures 1, 2) whereby the main pack on the moored profiler is replaced by a rechargeable one. Power is then delivered inductively to the profiler when it docks at a charger that is connected to a power source. At cabled nodes, this is essentially shore power. In the current application which is intended to be usable away from cabled sites, it is three 0.94m spheres filled with alkaline D cells. This therefore provides a means of delivering power to the profiler without the need to carry such large batteries on board, which would greatly increase its mass and drag.

Real-time two-way communications are also desirable for long-term moorings, especially when adaptive sampling is needed to resolve episodic events. We have implemented a communication system wherein data are transferred inductively from the profiler to a mooring controller and then to shore via a small “telebuoy” on the surface with RF and Iridium
satellite modems. An acoustic modem provided backup communications with a nearby ship in the event of loss or failure of the telebuoy.

We successfully deployed and tested the system in a 180-m-deep fjord and at station ALOHA, a 4748-m site 100 km north of Oahu, Hawaii. We demonstrated the full functionality of the system in both locations, but did not succeed in our goal of a one-year time series of profiles each hour and a half at the deep site. In spite of this, we describe the system and document our successes and failures since it has the potential to be useful in a variety of ocean applications including autonomous underwater vehicle (AUV) charging. We first describe the system, then the tests, then conclude.

2. System description

a. Overview

The basic concept was to modify a McLane Moored Profiler (MP), whose primary lithium battery pack allows one million vertical meters, with a rechargeable battery pack and an inductive charging system. This could in theory communicate with and be powered from a cabled seafloor observatory, but the current intention was to provide power and communication at uncabled locations by means of subsurface battery spheres and Iridium and radio-frequency modems on a surface float, with a subsurface acoustic modem for communication with nearby ships in the event of failure or loss of the float. Charging, communications and data acquisition were done from a subsurface mooring controller (SMC) housed in a cage. Communication between the MP and the SMC was via Seabird inductive modems, similar to ice-tethered profilers (Krishfield et al. 2008).
b. Experiment sites and mooring design

Station ALOHA, 100 km north of Oahu, Hawaii at 23.75N, 158W, was selected for the deployment site for scientific reasons including episodic cold overflow events from the Adjacent Maui deep (Lukas et al. 2001; Alford et al. 2011), strong and variable internal tides emanating from Kauai Channel (Mitchum and Chiswell 2000; Pickering and Alford 2012), and its colocation with the 27-year-long Hawaii Ocean Timeseries (HOT) program, obtaining ~ monthly ship-based full ocean depth sampling since 1988 (Karl and Lukas 1996; Lukas and Santiago-Mandujano 2001; Church et al. 2013; Karl and Church 2014). The monthly cruises conducted by the HOT program provided an important logistical benefit, allowing regular checkins to be be made on the mooring as well as acoustic modem data uploads when the surface float was not functioning.

As shown in a simplified mooring diagram (Figure 1), the mooring was located in 4748 m of water, with wire covering the vast majority of the distance. The subsurface floats housing the batteries were located between 50-60 m, with a 1.5m syntactic foam float for additional flotation above that. The system was recovered with dual Benthos acoustic releases. A small, light “telebuoy” extended upward and down current along the surface on an L-tether with a serial RS485 cable, and housed an Iridium satellite modem and Freewave radio-frequency modem.

Extensive system tests were also performed on a much shorter wire in 180 m of water in Puget Sound, a tidal estuarine fjord near Seattle, WA. The system was identical save for the length of the wire and the use of only one battery sphere.

c. Profiling vehicle

The McLane Moored Profiler (MP) is a proven profiling vehicle (approximately 200 systems sold) that employs a traction drive to crawl up and down a standard mooring wire. The standard instrument crawls at 25 cm/s – a balance between greater drag at higher speeds
and increased hotel load at slower speeds (Doherty et al. 1999) – and typically carries a conductivity-temperature-depth (CTD) instrument and an acoustic current meter (ACM) for velocity measurements.

The primary goal of our project was to extend the ≤ one million vertical meter endurance of the profiler by a factor of at least ten. Our approach was to replace the 2600 Watt-hour (Wh) primary pack with an 860-Wh rechargeable pack, and to periodically recharge it inductively from a charging dock mounted on the mooring wire, controlled by the SMC and powered by the battery spheres. Working together with McLane, additional electronics were added to the usual McLane controller to control charging and docking operations, as well as inductive communications. The rechargeable pack was housed in a third 12” glass sphere (in addition to the usual two for buoyancy), which required extending the length of the profiler. This modification increased the profiler’s mass and length, but not its cross-sectional area. Finally, the charging dock itself was added at the top of the instrument (Figure 2, left).

Because power was to be less of a concern, the gearbox ratio of the motor was reduced, giving a crawl speed of 33 cm/s instead of 25 cm/s, allowing a greater vertical aperture (about 1500 m) to be covered in an hour and a half, the longest one-way profile that reliably resolves the semidiurnal internal tides (Alford 2010). To balance full-depth coverage with tidal resolution, it was decided to sample from 100-1500 m for 400 profiles, then to do 14 profiles to 4000 m, and then return to the shallower profiling range. However, unfortunately, charging at ALOHA did not continue long enough to allow the deeper profiles.

d. Inductive Charging System

The inductive power transfer to the profiler is a key new enabling technical development of the project. The MP periodically connects or “docks” to the subsurface platform to charge its battery pack. Because the system components are submerged in conducting seawater, the connection must not use any contacts that allow an electrical connection to contact the seawater. Wet-mateable connectors that have enclosed, oil-bathed contacts have some
potential for this but they typically require a mating force of about 23 kg and have a limited
number of mate/de-mate cycles.

Inductive charging allows power to be transferred without electrical contact by modulating a current in a primary inductive coupler on the mooring, which induces a current on a concentric cylinder mounted on the MP, which we term the secondary coupler. This technology (Figure 2, middle) was demonstrated on the MP in a previous project intended for cabled applications (McGinnis et al. 2007; Howe et al. 2010); here, we modified the system for use with the battery spheres.

At the end of a profile triggered by either a low voltage or a preset number of profiles, the MP with the secondary coupler ascends and makes contact with the guide and coupler primary coupler. As soon as the primary and secondary couplers are engaged, as indicated by a limit switch, the MP motor stops and the system is ready for charging.

The direct-current to high-frequency-alternating-current (DC-HFAC) driver converts the battery spheres' 72 volts DC to a high frequency (50-70kHz) alternating current (HFAC) that can be transmitted across the inductive coupler interface. If the secondary coupler is not present, no current flows and the driver turns off. The system is electrically isolated at all times to prevent current flowing to seawater or the main mooring cable.

Since the most efficient frequency varies with the level of saturation of the coupler ferrite cores, the coupling efficiency is improved by varying the HFAC frequency over the charging profile. The shapes and mechanical design of the couplers need to allow reliable mechanical mating and inductive coupling between the primary and secondary and be tolerant of biofouling. Both the primary and secondary couplers are coaxial around the mooring cable to allow the MP to enter the dock at any horizontal orientation/heading.

Several precautions were taken to reduce the risk of dangerous outgassing of the batteries during charging. In order for any outgassing to occur, the batteries would need to be force charged with very high power and current that would require failure of 3 levels of protection circuitry to a short (as opposed to open) circuit. The first level is an active protection
module in the pack that senses and monitors voltage, current and temperature and controls
protection FET switches. The second level is an active thermal protection switching circuit
in the pack. The third level is a passive thermal protection device in the individual cells.
The most likely cause of outgassing would be having the pack punctured by some external
aggression. During testing and operation of several versions of the same inductive charging
system and Li-Ion battery pack, we never observed any evidence of outgassing. In the
unlikely event that any outgassing did occur, the glass sphere housing is only held together
by hydrostatic pressure and tape so if there was an over pressure in the housing, there is a
good chance that the housing would self-vent when it reached atmospheric pressure at the
surface before recovery.

The HFAC-DC Rectifier converts the HFAC power to direct current for charging the
battery. The Rectifier has a micro-controller that controls the battery charging voltage-
current profile appropriate for a Lithium-Ion battery. The charging starts out in constant
current mode and can supply a charging current of approximately 15A. When the battery
voltage reaches about 16.8V, the controller switches to a constant voltage mode. The system
is programmed to terminate the charge when the charging current drops below a set limit
of 5A.

The efficiency of the inductive power coupler is important for several reasons. Low
efficiency leads to long charge times, waste heat inside pressure cases and consumption
of the energy from the primary battery pack. Charge current varies as a function of the
coupler gap and input/output voltage (Figure 3a). It is clearly important to be sure the
profiler secondary core couples efficiently with the primary core on the cable. With a 2 mm
gap ≈280 W can be transferred (Figure 3b). The overall efficiency is about 68-71% (Figure
3c).
e. Battery Spheres

The power source for the HOT Mooring is provided by two steel spheres that each contain 36 packs of 48 series-connected D-cell alkaline batteries. Each cell has an initial and final voltages of approximately 1.5V and 1V, respectively, giving initial and final pack voltages of 72V and 48V. The 3456 alkaline D-cells have a total energy capacity of approximately 83kWh, enough to power the profiler for about 8 months (the original plan was for three spheres and a one-year endurance, but one was damaged on a recovery and was not redeployed). The batteries are mounted in two 0.94m steel spheres that have been constructed with off-the-shelf steel hemispheres that are used for large propane tanks. Water-jetted flanges are welded on to provide dual o-ring seals and to allow opening.

A trade-off study was done to select the optimal battery type/chemistry. The results of the trade-off study are summarized in Table 1. The two basic classes of batteries are rechargeable and non-rechargeable (primary). Rechargeable batteries obviously have the advantage of being recharged and reused, but are more expensive – even considering several reuses – and have a lower energy density. The main choices for primary batteries are Lithium and Alkaline. Lithium has approximately 2.5 times the energy density (by volume) but at 20 times the cost. Considering that the system would have multiple deployments – and battery pack replacements – Alkaline primary cells were selected for the sphere batteries.

f. Subsurface Mooring Controller

The Subsurface Mooring Controller (SMC) pressure case is mounted in a cage below the battery spheres and provides the system communication, command and control and the science instrument interfaces. The SMC is a custom designed circuit board that contains the CPU, load power switching, engineering data acquisition, program and science & engineering data memory and communications interfaces. The housing also includes the electronics for the inductive communication modem and the inductive power system.
g. **Communications**

1) **Data Rate**

The scientific data from the MP are sampled at about 2 Hz at 16 bits, such that the four CTD channels plus the 9 current meter channels take $(13 \times 16 \times 2) = 416$ bits per second (bps or baud). For 1.5-hour profiles, this amounts to about 281 KB of data per profile.

2) **Inductive Modem**

The SeaBird Inductive Modem (IM) system allows communication between the SMC and the MMP that both have an Inductive Modem Module (IMM) that is inductively coupled to the mooring cable using magnetic couplers. The IM system has a data throughput of approximately 700 bps and allows bidirectional science and engineering data and command and control communication during profiling. Two-way communications were not, however, implemented in the final configuration.

3) **Iridium Modem**

In normal operation, the Mooring Controller connects to an Iridium satellite modem on the surface with integrated GPS that allows data and configuration files to be transferred between the Mooring Controller and the shore data server at APL/UW. Because the data rate of the Iridium modem (2400 bps) is about 6 times the system data rate, all of the data generated in a day can be transferred in a reasonable amount of time (4 hours), costing allowing.

4) **Radio Modem**

As a higher-speed alternative and/or backup to the Iridium modem, the SMC also connects to a FreeWave radio modem on the surface to allow data and configuration files to be
transferred between the SMC and a vessel in the vicinity that has a compatible FreeWave radio modem. As part of the HOT time series, a research vessel visits the HOT site about once a month to make CTD casts and other measurements. While the ship is in the area, a technician on the ship can download data from the SMC. Due to the relatively high data rate of the radio modem (115 Kbaud), all of the data generated in the previous month can be transferred in a reasonable amount of time (a few hours; e.g. during a CTD cast).

5) **Telebuoy**

The Iridium and radio modems are mounted in the Telemetry Buoy, which has a serial RS485 data connection to the Mooring Controller through the tether, a 14-conductor cable with aramid strength member and 1/2” outer diameter. A number of small floats are clamped to the cable to maintain it in an “L” configuration. The buoy was designed to be light and inexpensive in the event of damage or loss by ship traffic or storms.

6) **Acoustic Modem**

The SMC was connected to an acoustic Woods Hole Oceanographic Institution (WHOI) Micromodem that allows data and configuration files to be transferred between the SMC and another acoustic modem on a nearby vessel in the event of loss or damage to the surface float. The ALOHA cabled observatory node will be located a few kilometers from the HOT Mooring Site and will have a 10kHz acoustic modem that could provide convenient continuous, real-time communications between the HOT SMC and shore. Due to the limited data rate and the relatively high power consumption of the acoustic modem, only a decimated data set can be transferred in a reasonable amount of time and energy.
3. Puget Sound tests

Figure 4 shows the first few days of engineering data from the Puget Sound tests. The system was deployed in about 180 m of water, and the MP programmed to alternate between 400 profiles from 35 and 120 m and 14 profiles from 35 m to 150 m (Figure 4d). At the beginning of the test, the vehicle’s rechargeable battery was drained to about 35% of capacity (about 15.3V) to reduce the time before a recharge would be required. The MP began profiling normally at 35 cm/s, returning to the dock when the voltage dropped below 15.2V. The charger turned on for one minute each 4 hours, a safety measure in case the profiler was attempting to dock but the proximity switch was not functioning. Upon docking, charge current increased to over 4A, causing the system voltage to dip under load to just over 60 V. The MP remained in the charging dock about 4 hours, exiting when the charging current dropped below 3A. At this time, its battery was about 70% charged (16.2V). It repeated this cycle approximately once a day for a week. Subsequent charges took less time (≈ 2 hours), increasing the profiler’s voltage about 0.5V each time. The associated duty cycle is 22h/24h=91.6%. Overall system voltage decreased over time as the float controller and charging slowly depleted the primary battery pack. Data were successfully transmitted back to shore in real time over the Iridium modem during the entire test.

After this period, the profiler was removed from the mooring for several days by divers and redeployed after reprogramming for less frequent charging. The system then remained in the water approximately 6 weeks (April 1-May 15), successfully charging 6 more times and collecting over 1550 profiles. The profiler was instructed to do a series of 14 deeper dives near April 6. Though not useful in the shallow water of Puget Sound, this capability was included to allow a limited depth interval to be sampled rapidly enough to resolve internal tides, followed by bursts of deeper sampling to gather deeper information at the expense of time resolution.

Scientific data from a representative 2-day period (Figure 5) show a clear low-mode internal tide with velocity amplitude of about 20 cm/s, and vertical displacements (seen in
density contours, black) of about 40-50 m. Profiles are every 20 minutes or so, such that the internal tides and higher-frequency internal waves are very well resolved.

4. Hawaii tests

The open-ocean test of the full system took place at Station ALOHA in July 2012 (Figure 6). Winds were 20-25 knots, mean and tidal currents were 0.4 m/s and 0.2 m/s, respectively, and waves were 4-7 m – a very different environment from Puget Sound. The rechargeable profiler batteries were initially drained as during the Puget Sound tests to ensure an initial recharge would occur while the ship was still in the vicinity. After deployment, the profiler began at 600 m, rising to 130 m and doing a down/up cycle before returning to the dock because of low voltage. Charge current was not recorded correctly during this deployment due to a software bug, but the primary sphere voltage dipped sharply as in the Puget Sound tests and the profiler voltage increased, indicating charging. The profiler left the dock when its voltage reached 16.2V, and did 12 profile pairs over about 2.5 days before attempting to dock twice. It did not successfully dock on either of these attempts, likely because of surface wave action coupled to the charging dock via the L-tether, but successfully docked on July 5, remaining in the dock about 6 hours as before and increasing the profiler battery voltage to about 15.5V. Charging did not complete, and the profiler made a number of subsequent attempts to dock, none of which were successful. It is likely that the profiler could not hold station at the dock in the presence of the surface wave pumping. Eventually the vehicle resumed profiling, continuing to do so until its batteries were depleted on July 9.

Scientific data from the Hawaii tests (Figure 7) show the strong southward surface mean flow modulated by tidal flows, which have a complicated vertical structure; these are associated with beams emanating from the Hawaiian Ridge (Pickering and Alford 2012).
5. Summary and Discussion

We have reported here on the design, construction and operation of a moored profiler system using an inductive power dock that periodically recharges a profiler from a large, fixed battery pack. The inductive dock transferred 225 W to the profiler with \( \sim 70\% \) efficiency such that the profiler could run at 35 cm s\(^{-1}\) with a \( \sim 90\% \) percent duty cycle (charging 2 hours, operating 22 hours per day). The total (alkaline) battery energy, 83 kWh or 300 MJ, was divided between two 0.94 m spheres. Real time inductive communication with the moving profiler was at 1200 bps. Communication between the mooring controller and the outside world was through three channels: An L tethered communication buoy on the surface provided Freewave (for a nearby ship) and satellite Iridium; further, an acoustic modem was used as well to communicate with the ship. There had been provision for the acoustic modem to provide a real-time connection to shore via the ALOHA Cabled Observatory, but the modem on the ACO had failed.

The system performed well in Puget Sound with the profiler moving between 35 and 150 m water depth over approximately 6 weeks successfully charging 6 times and collecting over 1550 profiles. Internal tides and higher frequency internal waves were well resolved.

The open ocean deployment at Station ALOHA with a water depth of 4748 m was less successful with two docking events and a total of 28 profiles. We suspect surface wave action was sufficient to interfere with the docking process. In the design process we had opted to charge at the top of the mooring as opposed to the bottom to avoid expensive pressure cases and the derating of alkaline batteries for the low temperature at depth. With hindsight, the much greater success in Puget Sound where surface waves are minimal suggest that charging at the bottom would have been a better choice, possibly with oil-filled lead acid batteries as the primary energy source.

Subsequent to this work, three “deep profiler moorings using this docking technology implemented at the bottom were deployed in 2014 on the NSF-funded Ocean Observatories Initiative Cabled Array (aka Regional Scale Nodes or RSN). The nodes are cabled for power
and high-speed communications. Data transmission to the cable is via the same inductive system as well as a local, very short range WiFi link when docked. The systems profiled and charged successfully from August to November, when a connector leaked causing a ground fault.

Another possible improvement would be to use a buoyancy engine to drive the profiler, similar to what is used on gliders and floats. For taut subsurface moorings in modest currents with minimal lean over, this should be more reliable as there would be no moving external parts (e.g., the drive wheel), and scalable to larger profilers and perhaps higher vertical speed. Such a vehicle was in fact built for this project, called the “Sea Tramp” by Ocean Origo. The vehicle was successfully tested in a Swedish fjord, but unfortunately had to be discontinued prior to the open ocean tests because the company went out of business.

Sustained collection of profiles of ocean data is a challenging problem. With these modifications and changes, the systems and techniques described here provide the potential for long-duration, rapid vertical sampling over much of the ocean water column, sampling physical, chemical, and biological quantities and telemetering them back in real time at uncabled locations.

Acknowledgments.

This work was supported by the National Science Foundation under award OCE-0647971. The authors wish to thank the engineers at the Applied Physics Laboratory’s Ocean Engineering Department – Chris Siani, Eric Boget, Vern Miller and Nick Michelle Hart – for their hard work and talent, without which this project would not have been possible. We thank the captains, Gray Drury and Rick Meyer, and the crew of the Kilo Moana, as well as the shore team at the University of Hawaii for their untiring support. Captain Meyer is to be particularly praised for his calm hand and steady leadership in keeping the crew and science party safe when the Kilo Moana began taking on water and had to be rescued by the Coast Guard during one of the deployments of the system. We also thank Roger Lukas
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