Project Number: 900723

Project Start: Jan. 1, **2007** **Project Duration (in years):** **1**

Please indicate what type of project is being proposed (mark only one).

X					
Feasibility/Scoping [Less than 100 days effort]	**Development**[1]	**Research**	**Infrastructure**[1]	**Education**	**Time Series**

Project Manager/PI: Andrew Hamilton

Project Title: Wave-Energy Extraction for Vertical Profiling Applications

[1] Development and infrastructure projects must complete the risk matrix (see item #5 at the end of the proposal form).

1) ABSTRACT (new projects only)

This is a proposal to examine the feasibility of extracting wave energy to power instrumentation on-board an upper-water-column vertical profiling platform. In several systems developed to date at other institutions, wave energy is used to drive the profiler up and down a mooring wire. In these systems, batteries are used for powering on-board instrumentation, limiting the profilers deployment duration and sample period. The effort proposed here is to investigate the feasibility of extracting wave energy to also power the instrumentation. Initial estimates indicate that it may be possible to extract more energy per profile than is used by typical instrumentation, allowing continuous profiling and much extended deployment durations.

There are several ongoing efforts to develop and refine profilers that utilize wave-energy for locomotion at other institutions. Therefore, this project is limited to investigating the development of a wave-energy extraction module that could be placed on-board existing and emerging systems, allowing more frequent profiling periods and to extend deployment durations.

The main activities and goals of this feasibility study are:

- Refine estimates of technical feasibility for extracting enough energy from wave motion to realize the possibility of continuous and unlimited profiling.
- Perform testing using the existing Seahorse system installed at Shepard Meander.
- Explore collaborations with groups currently developing wave-powered profilers so that technology transfer paths are identified before significant engineering development takes place.

2) PROPOSAL

a) Statement of the problem

Upper water column profiling is desired for many oceanographic investigations, but technology to reliably make long-term profiling measurements remains immature. A profiler to carry instrumentation through the upper water column that is suitable for long-term deployments (> ½ year) does not currently exist. The most convenient type of profiling system to meet this need is a profiler that would traverse the wire below a typical oceanographic mooring. Other techniques such as winched profilers or profilers that operate on sub-surface moorings have applications, but the need for a sub-sea power and/or data connection limit deployments to locations where such infrastructure is already in place.

A promising concept to realize this type of profiling platform is the wave-powered profiler which utilizes the motion of the mooring wire due to the wave-field to ratchet a buoyant profiler downwards to a specific depth. Once at depth, the measurement phase of the profile occurs as the profiler floats to the surface after disengaging the ratchet mechanism from the mooring wire. Several such wave-powered profilers have been developed and one version is commercially available (Seahorse, tested at MBARI, 2005-2006).

The wave-powered nature of these profilers is attractive because not only is no battery power used to move the profiler up and down the wire, but the profiling speeds can be much faster than is optimum for battery driven profilers. This higher speed reduces the time the instrumentation must be on, providing further energy savings. Nevertheless, the energy demands of the instrumentation limit current systems to deployments of about 100,000 meters of profiling. (i.e. a 200m profile every four hours for 3 months). Although this deployment duration could be extended by using higher energy density batteries or lower-powered instrumentation, extended high-frequency profiles can't be realized without including some type of battery recharging system.

The focus of the proposed feasibility study is to examine the development of a system to extract additional wave energy for the purpose of charging batteries and powering the on-board instrumentation. There is considerable energy in the wave field and the mooring wire naturally concentrates this energy and delivers it to the profiler. If a small percentage of this available energy is harvested on board the profiler to meet the instrumentation needs, continuous and indefinite profiling should be possible. If viable, this technology could enable a new class of profiling platforms that have truly long term deployment capability with minimal maintenance costs. In addition to extending deployments, if enough energy can be extracted from the wave-motion, the instrumentation payload of profilers could expand significantly, potentially enabling new profiling measurements and studies.

A drawback of the wave-powered profiling concept is that in calm conditions, no profiling takes place. Experience with the Seahorse profiler at the M0 site during a six month period indicates that about 9% of the hourly profiles were missed due to calm conditions. The average length of the calm period was about 2.7 hours, the longest period without achieving complete profiles was about 8 hours. It is conceivable that a wave-energy extraction device could operate in a reversible manner, converting stored electrical energy to locomotion force during calm periods. Thus the wave-energy concept proposed to be explored here has the possibility to extend the deployment duration, reduce the minimum profile frequency, and overcome short periods of calm wave conditions.

Solar and wind power are also candidates as supplies of energy to power instrumentation on the profiler, but would require energy transfer between the surface buoy and the profiler. Such a docking station may be feasible, but would need to be located below the buoy to avoid the need for electrical conductors in the mooring cable itself. Buoy and wave motions, combined with bio-fouling, make this location a very demanding environment for reliable operation of equipment. Furthermore, the time the profiler spends in the docked position will reduce the maximum possible profile frequency.

There are currently several wave-powered (locomotion only) profilers in development at other institutions. The most mature is the commercially available Seahorse profiler (www.brooke-ocean.com/s_horse1.html). This system was originally developed at Bedford Institute of Oceanography (BIO) and was commercialized by Brooke Ocean Technology. Although the concept of this system is sound, design and manufacturing issues have prevented the Seahorse from becoming a turn-key solution to below-buoy upper-water-column profiling. MBARI has tested this unit and integrated an inductive-modem based telemetry link for use in the MOOS Science Experiment at Shepard Meander. Battery limitations will require servicing of this system every 3-4 months. BIO has recognized the shortcomings of the Seahorse system and is currently working on a second generation version to address the reliability issues encountered with the first version. This second generation system will have a telemetry system based upon the newer Seabird inductive modem systems (which allows faster data transfer at lower power consumption than the original versions), but no plans are in place for in-place battery re-charging.

There have been other implementations of wave-powered profilers that fall into the prototype category, developed to demonstrate a technology or for a specific application. An example is an effort led by Hugh Milburn at PMEL who has integrated a prototype wave-powered profiler into the PICO mooring system. This mooring is a self-deploying mooring system that contains the mooring line spool inside the anchor module. Deployment is a matter of sliding the entire package off the side of a ship, the anchor drops away from the buoy, paying out anchor line as it goes and deployment is complete after a few minutes when the anchor hits the bottom. The aim of this project is to develop a oceanographic measurement buoy system that can be mass produced and is trivial to deploy, the aim being an order of magnitude reduction in the cost of many-buoy arrays. Because the self-deploying nature of this system precludes the use of discrete inductively-linked instrumentation typical of oceanographic moorings, the wave-powered profiler is included in the concept to provide profile data from the upper-water-column. The PICO system has been successfully deployed several times and would be a candidate for integration of the wave-energy extraction module should it progress beyond the prototype stage.

Because of these ongoing efforts at other institutions in developing wave-powered profiling systems, the plans for this feasibility study include an effort to explore possible collaborations with existing groups. Ideally, MBARI could develop a wave-energy harvesting module that could be placed on-board these existing profilers, relieving MBARI of the burden to develop, deploy and distribute a complete profiling system. In the absence of such collaborations, MBARI would have to decide upon the commitment to develop a complete profiling system itself if the wave-energy extraction concept appears promising after the feasibility study stage. One possibility at that point might involve integration with a past MBARI vertical profiling project (MVP). The hardware from this effort has enjoyed considerable operational success in recent years and many features of that system have proven effective. It may be possible that with some modification this hardware would provide a good test-bed for the wave-energy extraction techniques described here, providing a relatively low-cost path to a prototype of a fully wave-energy powered profiler.

This project fits into MBARI's mission and strategic plan by exploring technology that has the potential to change how oceanographic measurements through the water column are made. If successful, a new type of profiling instrumentation platform would be enabled that could provide truly long-term, unattended vertical profile measurements from below oceanographic moorings or drifters. The proposal specifically includes an effort to identify and explore possible technology transfer paths to ensure that this aspect of MBARI's strategic plan is met should this become a development project in the future.

b) Approach to the problem

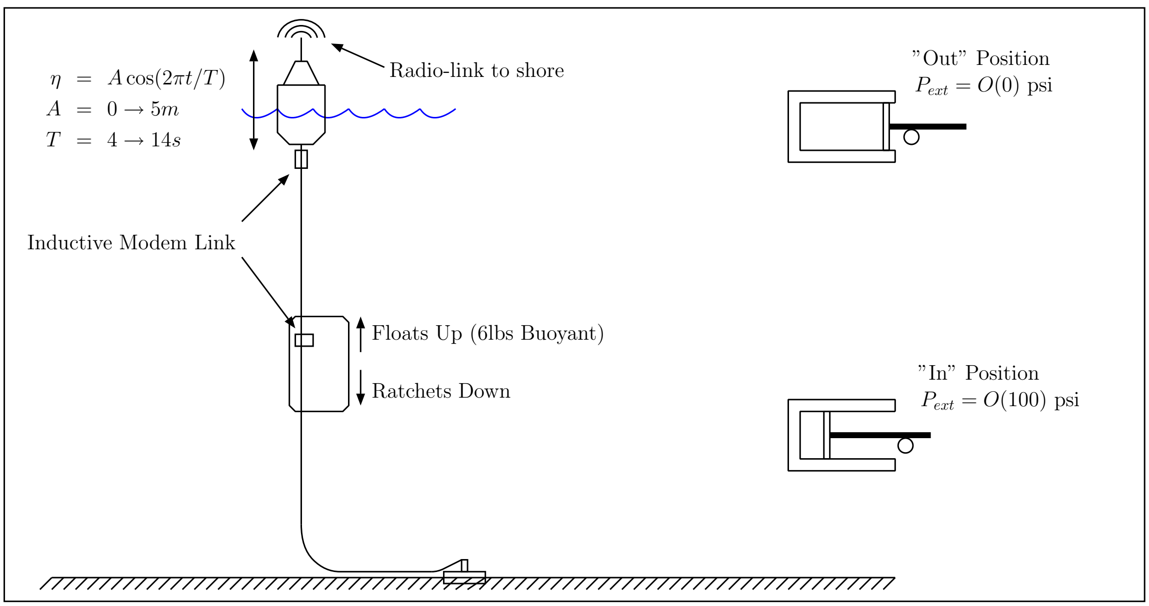

Figure 1: Arrangement of typical wave-powered profiler below surface buoy.

Figure one shows the usual arrangement of a wave-powered profiler below a surface buoy. Surface waves cause the buoy and mooring wire to bob up and down in a motion that nearly follows the surface wave elevation. The profiler is ballasted to be buoyant, and has a ratchet mechanism that clamps onto the mooring wire while it is moving downward relative to the profiler, but allows the mooring wire to move freely upwards. The profiler climbs down the wire when the wave motion is sufficient to overcome the buoyancy of the profiler, descent rates of 0.1 to 1.0 m/s have been observed in the Seahorse system. For the measurement phase of the profile, the instrumentation is turned on and the ratchet clamp is disengaged from the mooring wire. The buoyancy of the profiler causes it to rise back to the surface, the Seahorse is ballasted about 6 lbs buoyant and ascends at about 0.5 m/s. Figure two shows pressure data during the measurement phase for a typical profile executed at the M0 site. The 1m wave heights present were sufficient to drive the profiler to its bottom stop before the scheduled start of the profile, a pressure variation of about 1m can be seen at the beginning of the record followed by the smooth rise to the surface. Experience with the Seahorse has shown that the measurement phase of the profile is largely not influenced by the mooring wire motion.

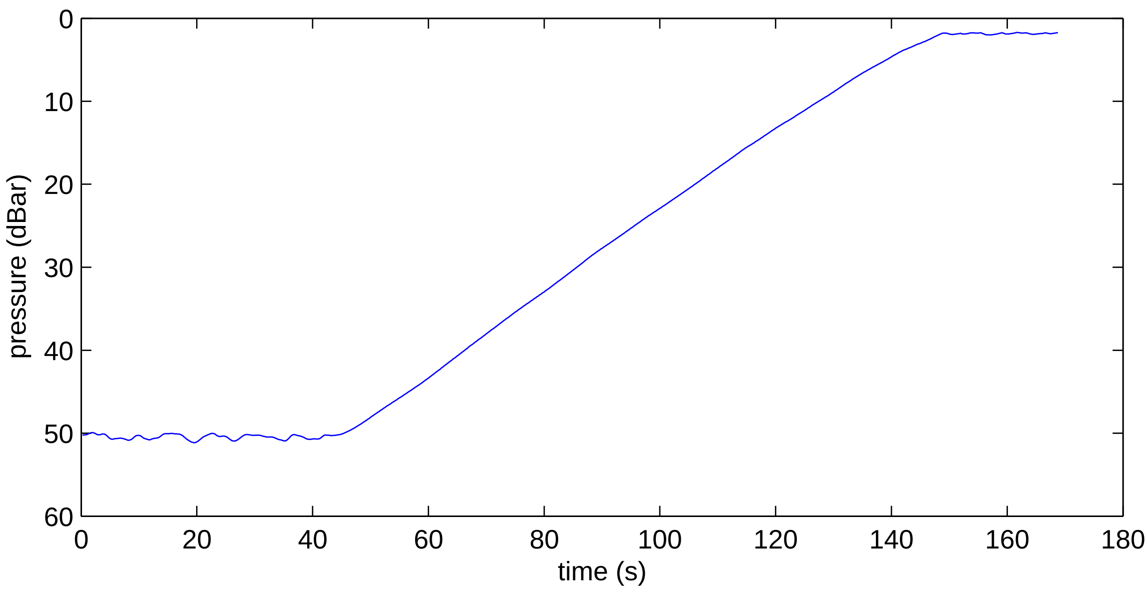

Figure 2: Typical depth profile showing smooth measurement phase, (~1m wave height).

There is considerable energy present in ocean surface waves, a wave field consisting of 1m wave heights contains 125 W/m^2, and the energy present grows as the square of the wave amplitude. This energy is split between potential energy related to the elevation of the wave itself and kinetic energy of the motion of the water in the waves. The kinetic energy is spread throughout the water column from the surface down to a depth of about ½ of the wave-length. The potential energy is located entirely near the surface. The mooring system effectively concentrates this energy and transmits it down the mooring wire to depths well below the region influenced by the waves, allowing a wave energy harvesting device on-board a profiler to be effective regardless of where the profiler is located on the mooring wire. Experience with MBARI's other deep-water moorings and numerical modeling of similar systems indicate that the mooring cables transmit wave energy very deep, significant motions have been witnessed as deep as 1500 meters and likely extend deeper.

A candidate technique for extracting wave energy and converting it to electrical energy on-board the profiler consists of a piston and lead-screw arrangement that converts pressure-volume (PV) work stored as the profiler descends to electrical energy. As shown in figure one, at the surface the piston would be positioned in the "out" position such that the internal volume of the piston would be evacuated and the profiler would be consequently more buoyant. As the profiler climbs down the wire, potential energy will be stored in this evacuated volume. Upon reaching the bottom of the profile, the piston will be allowed to move to the "in" position under the influence of the external hydrostatic pressure, the movement of the piston would cause a generator to turn through a lead-screw (or some similar arrangement), generating electricity to be stored for later use by the instrumentation.

In this concept the profiler will have to ratchet down against an additional buoyancy force that is proportional to the displacement of the piston. The magnitude of this additional buoyancy also dictates the potential energy that can be converted to electrical energy. Every additional pound of buoyancy submerged corresponds to 5 Joules per meter of downward travel. The Seahorse profiler uses about 6 Joules of energy per meter of profile to power its instruments. If the potential energy can be converted to electrical energy efficiently enough, an additional buoyancy of a few pounds would provide more energy per profile than is being used for the instrumentation, allowing continuous and indefinite profiling.

The mechanical-to-electrical conversion portion of the system must be optimized for efficiency, but is also constrained by weight, volume, cost, and other factors. The conversion system has the fundamental task of matching the available energy, which is high-pressure/low-volume PV work, to the characteristics of practical electrical generators, which are typically low-torque/high-speed devices. An initial approach would use an off-the-shelf permanent-magnet motor (80-90% efficiency), configured as a variable-frequency alternator, with output rectified and stored in a large capacitor (ultracapacitor). A lead screw and/or gear train (50-75% efficiency) could convert displacement (such as piston travel) to high speed rotation, accomplishing the required impedance match to the alternator mechanically. The electrical output of the alternator can be controlled electronically using a low-loss pulse-width-modulated regulator, in order to keep the powertrain at its most efficient operating point over the expected range of pressure and flow rates. Many aspects of the overall conversion system, such as mechanical speed, motor size, and power level (energy conversion rate) can be traded off against each other in order to optimize the system for minimum loss and minimum weight.

Other concepts for harvesting energy from the wave motion include a drag-device on the wire that turns a generator or a water-forced propeller that turns a generator. In each case the profiler will need to overcome an additional vertical force retarding it's progress down the wire, and the selection of technique should be based on which technique allows the most efficient conversion of potential energy represented by this force to electrical energy. The piston approach initially appears most attractive because energy from many wave cycles is accumulated as potential energy and then converted at once, potentially allowing higher efficiency because friction and other loss-effects can be minimized. Additionally, during low-wave conditions the energy extraction device can be disabled, or even reversed, to allow the profiler to return to the bottom more easily or under power.

There are currently two main unknowns in determining the feasibility of this technology. How much additional drag can the wave-powered ratchet mechanism tolerate, and how efficiently can the stored potential energy be converted to electrical energy. This feasibility study aims to answer these questions through a combination of analysis and testing. Although experience with the Seahorse system indicates that a few pounds of additional vertical force won't significantly impede downward progress, further testing is needed to accurately characterize the potential of the system. This testing will be performed using the Seahorse system that will be deployed at Shepard Meander in late 2006. A few Zephyr days will be required, and there is some potential for short term data loss from the profiler during the tests (hours or days). This testing part of the feasibility study would make an excellent intern project for summer 2007. An estimate of the conversion efficiency that is possible will also be established through analysis and some testing as part of this feasibility study. A simple prototype for laboratory testing of critical aspects of the conversion system will be developed using off-the-shelf components.

c) Specific deliverables

The feasibility study will conclude with a concept design review and report that outlines the technical feasibility of the wave-energy extraction concept based upon the results of the proposed analysis and testing. The report will identify the optimum conversion technique, report on the expected performance of a wave-powered profiler using this system and identify possible collaborations for technology transfer. If viable, a proposal for a development project would be submitted for funding in 2008.

d) Project team

Hamilton – Project management, mechanical engineering aspects of feasibility study, collaboration investigations.
Mellinger – Electrical engineering aspects of feasibility study.

e) Project lab space

No significant additional space will be required beyond the lab areas currently available to the project team members. (ME Lab, EE Lab).

3) BUDGET JUSTIFICATION (new and continuing projects)

Expense

- Supplies for buoyancy testing with Seahorse at Shepard Meander: $1000
- Supplies and equipment for conversion prototype testing: $5000

Ship Time

- Zephyr (3 days) for buoyancy testing with Seahorse. It's likely that these days can be combined with service trips to Shepard Meander.

Labor

- ME: 35 days (Hamilton)
- EE: 30 days (Mellinger)
- ME Tech: 10 days

- EE Tech: 10 days
- Machine Shop: 10 days

4) MILESTONES (new and continuing projects)

	Milestone 1	**Milestone 2**	**Milestone 3**	**Milestone 4**	**Milestone 5**	**Total Resources**[2] for each resource category for all milestones listed here
Milestone Date				**Aug 15**		
Milestone Description	**Analysis & testing of available energy (Seahorse testing)**	**Analysis & testing of conversion technique (Lab testing)**	**Collaboration exploration**	**Concept Design Review**		
EE	**5**	**20**		**5**		**30**
SE						
ME	**15**	**10**	**5**	**5**		**35**
Support Engineering						
EE Tech		**10**				**10**
SE Tech						
ME Tech	**5**	**5**				**10**
Machine Shop		**10**				**10**

[2] This number should be the same number you entered on the resource requests for this particular resource.