

Results From the First Successful Field Deployment of the McLane Moored Profiler

Archie T. Morrison III^{1,2}, John M. Toole², Roger Lukas³, Scott E. WorriLOW², and Kenneth W. Doherty²

¹McLane Research
Laboratories, Inc.

²Woods Hole Oceanographic
Institution

³University of Hawaii
at Manoa

Abstract

In advance of several anticipated one-year-duration deployments by Woods Hole Oceanographic Institution investigators, we deployed a production model McLane Moored Profiler (MMP) on January 9, 2001 for a short-duration trial on the southern flank of the Hawaiian Ridge. The mooring was placed in 2600 meters of water and the MMP was programmed to profile continuously between 600 dbars and 1600 dbars pressure. The system completed 62 profiles, as programmed, before recovery on January 13, 2001. The average profile duration was 75 minutes, during which the system logged a complete record of conductivity, temperature, pressure, ocean current, and system engineering information. The MMP and the sensors performed well during the trial, providing greater confidence for the year-long scientific deployments now being conducted.

A preliminary analysis of the engineering data gathered during the trial is presented here with discussions of zero-pressure rate detection, Strouhal oscillation, and power consumption. Fortunately, the sensor data collected during the trial have proven to be scientifically valuable. In particular, the MMP documented striking baroclinic tidal signals that are likely the product of the barotropic tide incident on the bathymetry of the Hawaiian Ridge. A portion of the sensor data will be discussed.

I. Background

Autonomous moored profilers supporting a suite of oceanographic sensors combine the advantages of long-term moored measurements of water properties and currents using discrete instruments at selected depths with those of short-term ship supported continuous profiling performed at high vertical resolution. The McLane Moored Profiler (MMP) is one such moored profiling sensor platform. The MMP is capable of making repeated vertical traverses of the water column and acquiring ocean property and current information at resolution comparable to that which is possible using manned research vessels over extended periods of time. The MMP has thus far been fitted with a Conductivity-Temperature-Depth (CTD) sensor and an acoustic current meter (ACM). Additional or alternate sensors can be integrated into the instrument suite. The MMP is being developed through a collaboration between the

McLane Research Laboratories, Inc. (MRL) and the Woods Hole Oceanographic Institution (WHOI). The goal of this collaboration is to make the profiler technology originally developed at WHOI accessible and useful to a broad cross-section of the oceanographic community. Side and top views of the MMP are shown in Figure 1. More complete descriptions of the WHOI and McLane profilers and their operation can be found in the references.

The short trial deployment described here was conducted to provide confidence in the MMP system in advance of several long duration science missions planned by WHOI investigators. Data acquired under field conditions were required to resolve questions about system endurance limits and hydrodynamic behavior in a varying horizontal current field. In addition, an earlier field trial had exposed a weakness in the zero-pressure rate algorithm. Verification that the parameter changes made to the algorithm had solved the problem was also sought.

II. Hawaiian Field Trial

We deployed a production model McLane Moored Profiler in 2600 meters of water on the southern flank of the Hawaiian Ridge on January 9, 2001. The location is west of Kaena Point in the Kauai Channel between the islands of Kauai and Oahu, the site of the Hawaii Ocean Mixing Experiment (HOME).

The profiling schedule of the MMP can be tailored, within limits, to fit the requirements of a particular investigation. Typically, the profiler is programmed with a periodic schedule of single profiles or up/down pairs of profiles. Paired profiles reduce the effects of bio-fouling by parking the vehicle at the bottom of the profiling range during periods of inactivity. The system can also be set for continuous profiling or for burst sampling. When burst sampling is selected, profiles are conducted in regular bursts of periodic profiles or profile pairs. The ability to conduct more complex patterns is planned for a later revision of the operating software.

For the Hawaii trial deployment the MMP was set for continuous profiling to maximize the distance traveled. In this mode profiles begin as soon as the data

collected during the previous profile have been stored. The short anticipated duration of the deployment permitted use of this mode without exceeding data storage or battery capacity limits. The 440 Mbyte flash card is sufficient for more than two million meters of travel with the standard suite of instruments. Battery capacity and system endurance are discussed in Section V.

The excursion limits of a profile, shallow and deep pressure levels, are set by the operator. The profiler normally terminates a profile when the target pressure is reached, however, pressure rate, depth relative to physical stops on the mooring, elapsed time, and several engineering parameters are also monitored and used to control profiler actions [Morrison, et al., March 2000, Morrison, et al., October 2000]. For this trial the MMP was programmed to travel between 600 dbars and 1600 dbars pressure, an interval determined by the available length of mooring wire.

The MMP had completed 62 profiles and a portion of a 63rd when the mooring release was triggered on January 13. The completed profiles are numbered 0 to 61. Even numbered profiles proceed from shallow to deep. Profile 0 begins after a programmable delay to allow for deploying the mooring. It ends at the deep pressure limit, but has an arbitrary start depth that depends on the actual setting of the mooring and on vehicle ballasting.

This was a very clean and largely successful field trial. The profiler and the sensor systems performed well, providing valuable information about system performance under field conditions and lent confidence to the subsequent year-long scientific deployments. Portions of the engineering and sensor data gathered during the deployment are presented below with discussion of their implications and some possible improvements. Fortunately, the sensor data collected during the trial have proven to be scientifically valuable. In particular, the MMP documented striking baroclinic tidal signals that are likely the product of the barotropic tide incident on the bathymetry of the Hawaiian Ridge. A portion of these data will also be discussed.

III. Zero-Pressure Rate Algorithm

The zero-pressure rate algorithm is used to detect obstructions on the mooring wire that block passage by the MMP. It also allows the system to identify the physical stops placed on the mooring to constrain the range of the vehicle. The selection of time and rate thresholds for detection was originally based on the ± 1 dbar accuracy of the CTD pressure measurement and the 25 cm/s nominal profiling speed of the MMP.

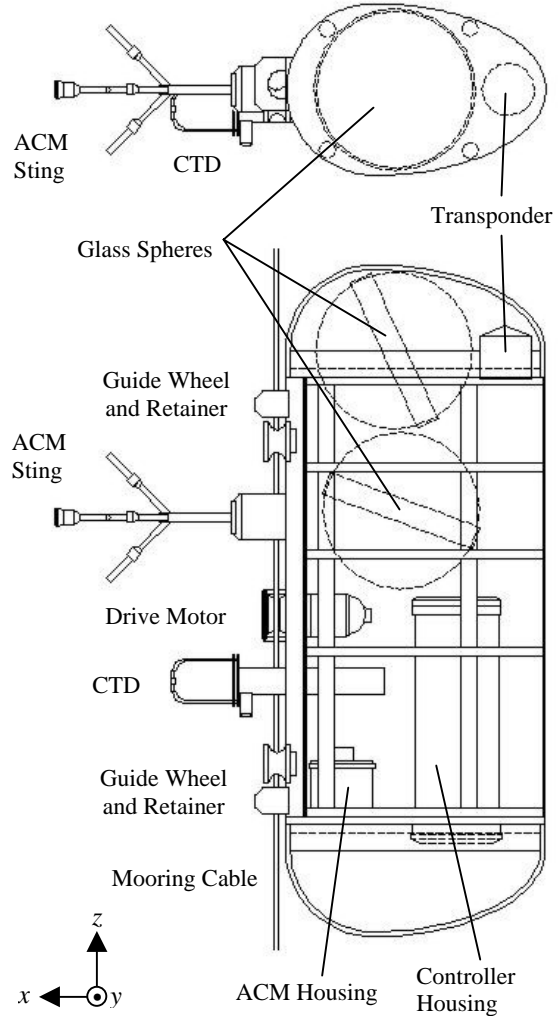


FIGURE 1 – SIDE AND TOP VIEWS OF THE MMP. The overall dimensions of the faired, free flooding, external shell are 124 cm \times 51 cm \times 34 cm. The vehicle self-orients to point the ACM sensor head ("sting") into the horizontal flow. The vehicle Cartesian reference frame is defined as shown, with the y -axis having the usual right-handed sense. u , the x -axis component of the velocity, is typically negative in this system.

Those parameters did not, however, sufficiently filter the pressure rate variations caused by mooring motion. Numerous false detections of tether obstructions occurred during an earlier field trial near Bermuda. Further complicating the failure was the presence of a coding error in the subroutine guiding the system's response to an obstruction. A thoroughly compromised data set was the result.

The coding error, once identified, was eliminated and the intended response to obstacle detection, a series of back-ups and retries to pass the obstruction, was confirmed on the bench and in the 17 m MRL test well.

It remained, however, to significantly reduce the false detection rate for realistic field conditions, conditions that we could not accurately duplicate in the laboratory.

During the Hawaii trial, the measurement of dP/dt was made over a longer minimum time interval with a lower rate threshold. Specifically, the minimum time interval was increased from 20 seconds to 3 minutes and the rate threshold was reduced from 0.125 dbar/s (12.5 cm/s) to 0.045 dbar/s. The new parameters are identical to those used successfully in the WHOI Moored Profilers [Doherty, et al., 1999]. The form of the algorithm is the same in both profilers. However, the WHOI profiler uses an analog pressure transducer, averaging many rapidly acquired measurements to achieve a differential accuracy of 1.5 dbar over a 6000 dbar range. The McLane profiler uses the CTD pressure with a differential accuracy of 0.1 dbar to 0.3 dbar over a 7000 dbar range with ~ 0.5 s uncertainty in the time of a measurement.

There were no detections of a zero-pressure rate during the Hawaii deployment until the release of the mooring anchor during Profile 62 left the vehicle suspended at a fixed depth. The algorithm was able to detect a low pressure rate when it occurred, but did not respond to the short duration changes associated with mooring motion. It should be noted, however, that the MMP was not subjected to severe mooring motions during this trial. It may be necessary to revisit this issue in the future, particularly as profilers move into the energetic surface wave zone. However, given the well established record of the parameters used in the WHOI profiler, the similarity of the measurements and algorithms, and the behavior observed in this trial, we feel reasonably confident that this is a solved problem.

IV. Strouhal Oscillation

The MMP used in Hawaii is a production model copy of the third prototype frame designed and built during profiler development at MRL. The first prototype was box shaped with rounded corners and edges. It had a reasonably low coefficient of vertical drag and was easily handled during launch and recovery. However, it was observed during dock tests, in horizontal currents of 20 cm/s to 30 cm/s, to be susceptible to quite severe oscillations when parked. The oscillations had a period of ~ 5 s to ~ 10 s and an amplitude of $\pm 30^\circ$ to $\pm 45^\circ$. The "wagging" was reduced during a profile; we believe that was a result of the vehicle being able to move out of its own horizontal wake during a single period of vortex shedding.

The second prototype was similar in shape to the current production model. The shape was selected for low drag throughout the range of relative flow angles

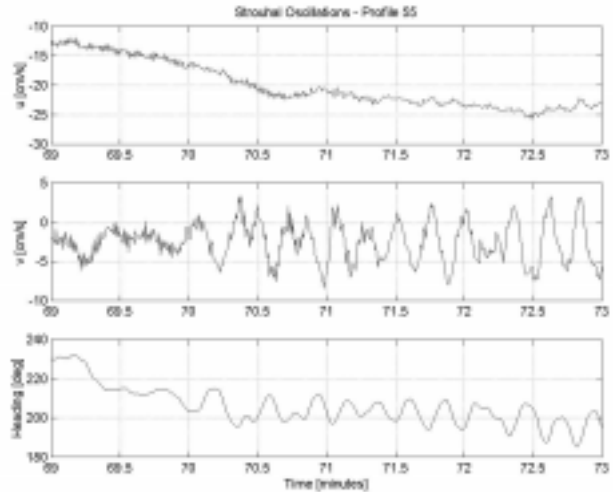


FIGURE 2 - STROUHAL OSCILLATIONS DURING PROFILE 55. The three panels show 4-minute records of the horizontal components of velocity and vehicle heading as the MMP traveled from ~ 750 dbars to ~ 700 dbars shortly before the end of Profile 55. Oscillations in the heading record begin as the magnitude of u , the incident horizontal flow, exceeds ~ 15 cm/s. Note the resulting contamination of v , the lateral component of the flow.

that the vehicle might encounter moving vertically in a largely horizontal velocity field [Morrison, et al., March 2000, Morrison, et al., October 2000]. Unlike the third prototype and the production model, the port and starboard leading edges of the skin covering the frame of the second prototype were not recessed in machined grooves. The second prototype was also observed during dock tests, though in weaker currents (< 20 cm/s). It was stable both while stationary and while profiling during those tests. The third prototype, with recessed edges, a smoother cross-section, and fairing of most protrusions, was observed at the dock only in very weak currents (< 10 cm/s). There was no evidence of oscillation observationally or in the compass record of the acoustic current meter.

In the data from the Hawaii trial however, there are many clear examples of Strouhal oscillation occurring whenever the relative horizontal velocity exceeds 12 cm/s to 15 cm/s. The presence of wagging contaminates the velocity measurements. A first order correction for sensor motion reduces, but does not totally eliminate, the error. An example is shown in Figure 2.

The Reynolds number for the latter half of the 4-minute records shown in Figure 2 is $O[10^5]$, indicating a laminar boundary layer around the vehicle with some transition to turbulence in the wake. The accepted value of the Strouhal number for a long cylinder under these conditions is 0.2. Blevins cites a Strouhal value of 0.18 for a sphere at $Re=10^5$. It seems reasonable to

expect the MMP to fall somewhere in that range.

When the speed of the incident flow is ~ 23 cm/s, the oscillations have a period of ~ 15 s and an angular amplitude of $\pm 7^\circ$. The frequency of oscillation is slower than would be predicted using the 35 cm cross-flow or the 50 cm along-flow dimension of the MMP and a Strouhal number of 0.18-0.2. The frequency implies a characteristic length of 60 cm to 70 cm. Blevins suggests, however, that the pertinent length scale for Strouhal oscillation is the width of the wake, not one of the body dimensions. The vehicle is free to pivot in response to Strouhal forcing and wagging tends to move the flow separation location forward, widening the wake and lengthening the period of oscillation [Blevins, 1984]. A wake width of 60 cm to 70 cm is not unreasonable.

The vertical motion of the vehicle, which moves three times its own length during one period of oscillation, appears to weaken the strength of the oscillatory forcing, although the frequency of the forcing does not change. The MMP logs sensor data while not actively profiling for two minutes at the beginning and end of each profile. Oscillations recorded during these intervals have the same frequency as those recorded while moving vertically (for the same horizontal velocity, the quantities scale linearly), but a somewhat larger amplitude. For example, oscillations during the stationary interval at the end of Profile 7, forced by an incident flow of 14 cm/s, have a period of 25 s, a characteristic length of 60 cm to 70 cm, and an angular amplitude of $\pm 10^\circ$. This is also consistent with the observation of increased stability in flight made during the dock tests.

Why didn't the second and third prototypes, with the same faired shape used in the production model, exhibit Strouhal oscillations during dock testing? In the case of the third prototype, the tidal flow past the dock was simply never strong enough to excite wagging. The second prototype, however, was exposed to flows that exceeded the 10 cm/s to 15 cm/s threshold of the Hawaii trial.

We hypothesize that the un-recessed leading edge of the second prototype's skin is the significant difference. The raised edge of the skin served as a fixed trigger point for symmetric boundary layer separation, inhibiting the formation of the alternating wake vortices that give rise to Strouhal oscillation. In this sense the production model of the MMP is "too smooth". The boundary layer remains attached well around the curve of the profiler cross-section and the port and starboard separation points are able to move freely back and forth along the surface as trailing vortices form and separate. That freedom of movement allows the formation of a von Karman street of alternating vortices.

Our hypothesis is supported by the Strouhal history of the WHOI Moored Profiler. The initial shape of the MP was fully faired and subject to wagging. When the forward fairing was removed to relieve a problem with guide wheel fouling, a sharp leading edge was exposed and Strouhal oscillations ceased to be a significant problem [Doherty, et al., 1999, Toole, et al., 1999].

The intent in smoothing the cross-sectional shape of the McLane profiler was to increase mission endurance by reducing hydrodynamic drag. We have, perhaps, succeeded too well. It seems obvious now that a trigger point for boundary layer separation should be re-introduced. To this end we have added port and starboard vertical ribs to three production model MMPs, all currently deployed by WHOI investigators. The ribs have a triangular cross-section ~ 1 cm on a side and are mounted ~ 5 cm behind the recessed leading edge of the skin. The ribs will, we think, force a fixed, symmetric, separation of the boundary layers and suppress Strouhal oscillation. There will probably be some increase in horizontal drag, which is of some concern (see Section V). We are planning a tow tank study to test this modification and to investigate the optimal placement of the ribs for suppression of the oscillations with a minimal increase in drag. We hope to report on the success of this approach in a future paper.

V. Power Consumption

McLane Moored Profilers are normally deployed with a 24 cell lithium battery pack. The standard pack has a capacity of 240 Ahr and operates at 10.8 Volts. The Hawaii trial was conducted using a 50 Ahr, 10.5 V (open circuit), alkaline battery pack. The alkaline pack was selected simply because preparation time was limited and we could not easily have met the shipping requirements associated with large lithium batteries.

Profiling speed depends on battery voltage. At the beginning of the deployment the alkaline pack was able to deliver 10.2 V under load and the average profiling speed was 24.4 cm/s. By the end of the deployment the voltage under load had dropped to 8.6 V and the profiling speed was 20.5 cm/s. The standard lithium pack supplies a steady voltage under load of 10.8 V for 90% or more of its life. The nominal profiling speed at that voltage is 25.5 cm/s. Motor current depends, largely, on the hydrodynamic drag, which is proportional to the square of profiling speed. We are concerned here with the consumption of energy from the battery under field conditions, so it is the record of motor current from the earliest profiles with which we are most concerned.

The data indicate that motor current is also affected

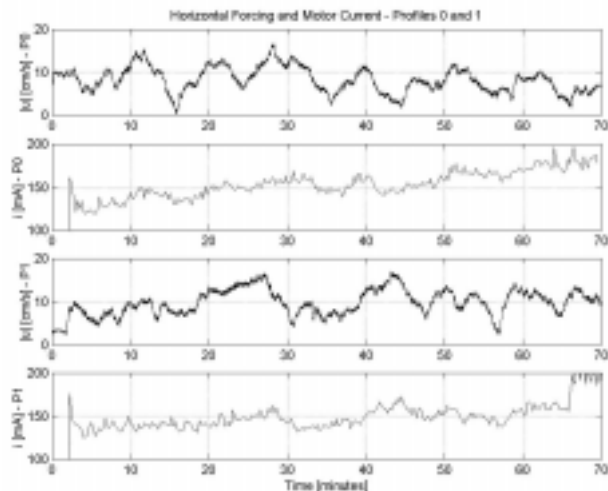


FIGURE 3 - HORIZONTAL FORCING AND MOTOR CURRENT. The first and third panels show the magnitude of u , the incident horizontal current, during Profiles 0 and 1. The second and fourth panels show the corresponding records of motor current. Note the positive correlation of motor current with forcing strength. The average motor current is 150 mA.

by horizontal forcing (drag). The effect is somewhat greater than we had expected. There is a clear positive correlation between the motor current and the magnitude of the horizontal velocity field (Figure 3). It is our belief that stronger forcing increases the deformation of compliant elements such as the cable jacket, the guide wheels, and the guide wheel bearings. The larger deformations increase rolling friction and thus raise the motor current. This will be a consideration for the use of the stabilizing ribs discussed in the previous section, a modification that is likely to increase horizontal drag. Not surprisingly, Strouhal oscillation, which also increases horizontal drag, observably increases motor current in the record. Internal waves, surface swell, and other environmental forcing, will all contribute to a varying load on the motor and should be considered when making a realistic estimate of the average current drain during a deployment.

The average motor current for Profiles 0 and 1 was 140 mA. The average motor current for Profiles 30 to 61 was 130 mA. This is consistent with anecdotal observations of the WHOI profilers, which generally exhibited "wearing in" behavior each time they were deployed. It is also consistent with the slower profiling speeds at the end of the deployment. Profiles 2 to 29, however, had average motor currents of 210 mA and exhibited greater variability around that average than during the later profiles. The strength and suddenness of the dichotomy are striking (Figure 4). Depth-averaged ocean speed varied over the course of the deployment from near zero to more than 15 cm/s, but

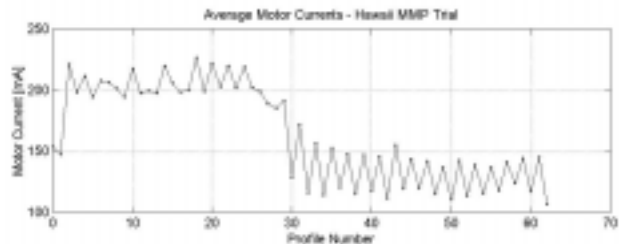


FIGURE 4 - AVERAGE MOTOR CURRENTS - HAWAII MMP TRIAL. The trace shows simple averages over the motor current time histories logged in the engineering data. The high currents early in the trial suggest fouling by detritus. The up/down asymmetry of the later profiles indicates ballasting was mildly heavy.

the variations did not correlate with the motor current anomaly. It seems probable that the MMP acquired and then lost some detritus that had fouled the mooring cable while it was being deployed. Note that the profiler was able to continue the mission, albeit with a greater drain on the battery. Under the circumstances, we have chosen to use Profiles 0 and 1 as a baseline for motor current. The initial motor current in both cases was ~ 120 mA. The motor current climbed steadily in each case, reaching ~ 170 mA by the end of the profile. The average current drain in both directions was ~ 140 mA (Figure 3). This is higher than the 100 mA to 120 mA range commonly observed in the MRL test well, an environment with no horizontal forcing.

The motor current varies over the course of a profile because of changing buoyancy forces; the MMP is less compressible than seawater. The vehicle was ballasted to be neutrally buoyant at the mid-point of the profiling range. The average motor currents for Profiles 30 to 61 show approximately 30 mA of asymmetry, indicating that the ballasting was mildly heavy, but fairly accurate (Figure 4).

A realistic assessment of mission endurance should assume moderate average forcing. The Hawaii trial indicates that 140 mA is a fair value for the motor current. A larger value is advisable during planning if severe conditions are expected. Note that this is a higher current drain than would have been assumed based on our experience in the test well. Horizontal forcing has a stronger effect on motor load than we anticipated and should be considered during deployment planning. The result also shows that the MMP is actually operating well away from the optimal 2:1 ratio of hotel load to locomotion load [Morrison, et al., March 2000, Morrison, et al., October 2000].

The current drains of other system components have been measured on the bench. The CTD requires 12.5 mA while logging internally (profiling) and 30 mA while moving data onto the flash card at the end of a profile. The comparable drains for the ACM are 25 mA

and 40 mA. The micro-controller requires 2 mA while active and 0.5 mA in low power sleep. Most of a deployment is spent in the latter condition. On average this means a total drain from the battery while profiling of 180 mA to 200 mA under field conditions. During data storage, 10% to 15% of the elapsed profile time, the drain averages 50 mA.

We conclude, based on these measurements, that the endurance of a production model McLane Moored Profiler equipped with a 240 Ahr lithium battery is 1.1 to 1.2 million meters.

VI. Baroclinic Tidal Signals

The Hawaiian Ridge represents a significant bathymetric obstruction to the barotropic tidal flow between Oahu and Kauai. As such, the region is a natural laboratory in which to investigate barotropic tidal scattering into baroclinic motions, a key element of the Hawaii Ocean Mixing Experiment (HOME, <http://chowder.ucsd.edu/home/>). The MMP trial described here has fortuitously contributed to the HOME program by providing a short, but temporally and vertically well-resolved sampling of the internal wave field above the flank of the Ridge. The tidal flows, constricted by the island chain and the Ridge, are accelerated to speeds approaching 30 cm/s at certain depths and times (Figure 5). Accompanying the strong tidal currents are peak-to-peak vertical displacements of isopycnals of ~ 100 m (Figure 6). The isopycnal heaving is, by definition, a baroclinic wave; the observed horizontal currents appear to be a mixture of barotropic and baroclinic motions. There is a significant correlation between the meridional flow and the vertical displacement evident in the figures, indicative of horizontal energy flux by the internal tide [Merrifield et al., 2001 and references therein]. Also of interest in the velocity plot is an indication of upward phase propagation in time. For an individual free internal wave in the northern hemisphere this implies downward energy propagation. Perhaps we are observing a surface reflection of an internal tidal wave generated at the Ridge crest. Alternatively, this could be the manifestation of a superposition of many wave modes. To sort this out, we plan a joint analysis of these ocean data with the numerical model of Merrifield et al. run for the same time period as the MMP deployment.

VII. Conclusions

Given the good performance of the McLane Moored Profiler described here and the past successes of WHOI prototype systems, we feel the Moored Profiler is now

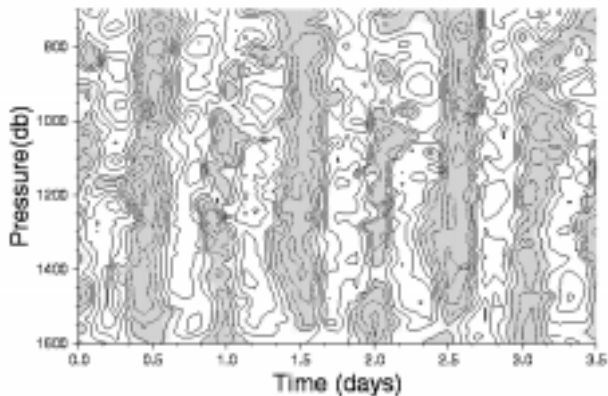


FIGURE 5 - MERIDIONAL (NORTH-SOUTH) ABSOLUTE VELOCITY. The raw MMP profile data were binned to 10 dbars and 1.5 hours before contouring. The contour interval is 5 cm/s with negative (southward) isolines shaded gray. The meridional component of the velocity is nearly orthogonal to the axis of the Hawaiian Ridge axis.

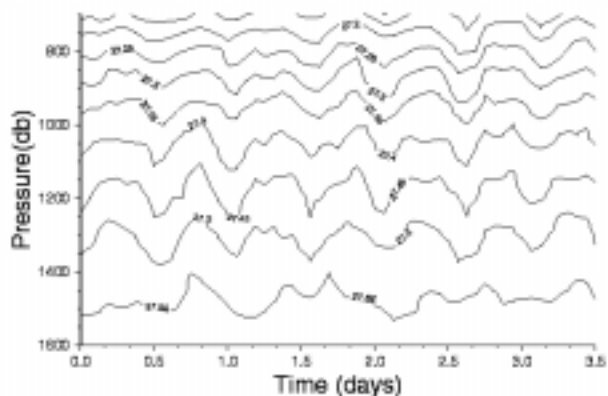


FIGURE 6 - POTENTIAL DENSITY ANOMALY (REFERENCED TO THE SURFACE). The raw MMP profile data were binned to 10 dbars and 1.5 hours before contouring. The contour interval is 0.05 kg/m³.

making the transition to an operational oceanographic system. By the time of the OCEANS 2001 Conference, a total of seven MMPs and three WHOI MPs will be deployed in the ocean on year-long missions in support of U. S. and overseas investigators. Deployments of at least two more MMPs are being planned for the fall and winter of 2001.

To facilitate access by the research community to this new technology, a shared-use instrument pool has been established at the Woods Hole Oceanographic Institution. Interested users are encouraged to contact WHOI (jtoole@whoi.edu) for information about the Profiler pool. Operational and performance information for the MMP is available from McLane Research (mclane@mclanelabs.com). MRL also offers a hands-on training course in MMP operation at their facility in East Falmouth, MA.

Acknowledgments

We wish to extend our thanks to Steve Liberatore, John Kemp, Ryan Schrawder, and Dan Frye of WHOI, and Roy Smith, Dick Koehler, John Billings, Ivory Engstrom, and Dave Bernklow of MRL, for their contributions to the WHOI and McLane Moored Profiler projects and to the success of the Hawaii trial. Thanks also to Fernando Santiago and Tim Finnigan, co-chief scientists on the cruise, and Mark Valenciano in Hawaii, for technical assistance before and during the cruise. Finally, our thanks to Ellyn Montgomery of WHOI for her assistance processing sensor and engineering data for this paper.

The WHOI Moored Profiler was initially developed with the support of the National Science Foundation through grants OCE9320647 and OCE9617072. Subsequent work was funded by the Office of Naval Research under Grants N00014-95-1-1001, N00014-97-1-0087, and DURIP Award N00014-97-1-0378 and by the NOAA-University Consortium. WHOI personnel were supported by the National Science Foundation through grant OCE0083268 while conducting the Hawaii MMP trial. The development of the McLane Moored Profiler was underwritten by the McLane Research Laboratories, Inc. This paper is WHOI Contribution No. 10504.

References

- Blevins, R. D., *Applied Fluid Dynamics Handbook*, Van Nostrand Reinhold Company, Inc., New York, NY, 1984, pp. 339.
- Doherty, K. W., Frye, D. E., Liberatore, S. P., Toole, J. M., “A Moored Profiling Instrument”, *Journal of Atmospheric and Oceanic Technology*, Vol. 16, pp. 1816-1829, 1999.
- Merrifield, M. A., Holloway, P. E., Johnston, T. M. S., “Internal tide generation at the Hawaiian Ridge”, *Geophysical Review Letters*, 28, 559-562, 2001.
- Morrison, A. T., III, Billings, J. D., Doherty, K. W., Toole, J. M., “The McLane Moored Profiler: A Platform for Physical, Biological, and Chemical Oceanographic Measurements”, *Proceedings OCEANOLOGY International 2000*, March 2000, pp. 397-414.
- Morrison, A. T., III, Billings, J. D., Doherty, K. W., “The McLane Moored Profiler: An Autonomous Platform for Oceanographic Measurements”, *Proceedings of OCEANS 2000*, MTS/IEEE/OES, October 2000, Vol. I, pp. 353-358.
- Toole, J. M., Doherty, K. W., Frye, D. E., Liberatore, S. P., “Velocity Measurements from a Moored Profiling