The McLane Moored Profiler:
A Platform for Physical, Biological, and
Chemical Oceanographic Measurements

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Abstract

   The McLane Moored Profiler (MMP) is an autonomous, profiling, instrument platform developed as a collaboration between the McLane Research Laboratories, Inc. (MRL) and the Advanced Engineering Laboratory and the Department of Physical Oceanography of the Woods Hole Oceanographic Institution (WHOI). Our goal is to make moored profiler technology available to, operable by, and useful to a broad cross-section of the oceanographic community. The platform and software are designed for ease of access, operation, and maintenance. The baseline instrument suite includes both a CTD and an acoustic current meter. Provisions have been made in the design for a variety of additional instruments, including commonly available bio-optical and chemical sensors. The engineering development is nearing completion with laboratory, dockside, and open ocean tests currently underway. This paper documents the design of the platform and presents the results of performance trials undertaken to date. Open ocean data obtained by WHOI prototype profilers are included to demonstrate some of the capabilities of these instrumented platforms.

I. Background

   The archetypal physical oceanographic measurement is the CTD profile. This measurement is so important to the pursuit of oceanography that virtually all research vessels have the ability to make such a cast and profiling is an integral part of daily operation on the vast majority of research cruises. Today the profiling platform suspended from the hydrowire of a research vessel often includes not only a CTD and water sampler, but also an integrated suite of acoustic current profile, bio-optical, chemical, and suspended material sensors. The integrated nature of the data stream available from these platforms makes it possible to study the interactions and dependencies of a broad, multidisciplinary spectrum of ocean processes, but only at a single location and only for a relatively brief span of time. It is a truism of oceanographic research that our growing understanding of the oceans is constrained less by sensor technology than by the extent to which we can deploy that sensor technology over diverse spatial scales and longer time intervals. Autonomous instruments, bottom landers, drifters, and static moorings making measurements at several discrete points have all made (and continue to make) important contributions to the ongoing

process of understanding the oceans. However, these approaches lack the fine scale resolution of the continuous cast made from a research vessel.

Acquiring a long time-series at high vertical resolution is a natural and desirable next step, but the cost and difficulty of keeping a ship on station for long periods of time have effectively prohibited this advance. Trying to obtain multiple, simultaneous time-series of casts from several related locations, while desirable, simply compounds the difficulty. Notable exceptions are the Ocean Weather Stations established after World War II [Dinsmore, 1996] and "Station S", established offshore of Bermuda in 1954 [Michaels and Knap, 1996]. The OWS time series played a critical role in early efforts to understand ocean variability and its response to atmospheric forcing. The established importance of these data sets to ocean science amply demonstrates the importance of collecting and continuing to collect time-series data.

Fortunately, the technology is now available to perform the task without ships by using autonomous vehicles, in particular, moored profilers. Research groups and companies from several countries have undertaken the development of these platforms. One particularly successful vehicle is the Moored Profiler developed at the Woods Hole Oceanographic Institution (WHOI) by members of the Advanced Engineering Laboratory of the Department of Applied Ocean Physics and Engineering working in collaboration with members of the Department of Physical Oceanography. The Moored Profiler has demonstrated through a number of dockside and open ocean trials and experiments that this technology has arrived. Data sets of CTD and current velocity profiles covering periods of several months to a year have been produced and an endurance of one million meters has been demonstrated [Doherty, et al., 1999, Toole, et al., 1999]. Application of this technology on a broader scale by a larger and more diverse group of investigators is an obvious direction in which to proceed. The benefit to ocean science is enormous.

However, several aspects of the prototype Moored Profiler design make production and wide spread use by the oceanographic community rather problematic. First, the instrument and battery housings are glass spheres. Glass spheres are lighter and less expensive than metal housings and are not subject to corrosion. They also match the compressibility of seawater more closely. Unfortunately, glass spheres are more susceptible to damage during handling than metal housings and can spall or leak if imprecisely positioned while being sealed and evacuated. The spheres in the Moored Profiler must be serviced, sealed, and evacuated prior to each deployment and then opened after recovery to offload the data and replace the batteries. This is a painstaking job and should only be performed by trained and experienced personnel. Other limitations are inherent in the prototype Moored Profiler's controller. This module is based on an obsolete micro-controller for which there are no longer any sources. Although the module is fairly reliable, no more of them can be built. Moreover, all available program space is already in use and processing and I/O capabilities have reached their limits in this configuration. New features such as a more flexible user interface, system and sensor diagnostics, and additions to the instrument suite are not possible. Finally, experience has shown that the shell of the Moored Profiler is difficult to fabricate with the repeatability necessary for production units.

The McLane Moored Profiler (MMP) is a commercial development undertaken by the McLane Research Laboratories, Inc. (MRL) in association with the Moored Profiler team at WHOI. The new design incorporates the proven features and technology of the WHOI

Moored Profiler, addresses its known shortcomings, and benefits from the knowledge and experience of the original design team. The new platform can be manufactured in small quantities at reasonable cost. It can be successfully operated and maintained by a general user without special training or great difficulty. The user interface allows flexible deployment scheduling and supports system and sensor suite testing and diagnostics. The electronics and controller are able to accommodate new features as needed, including a variety of additional sensors.

Section II of this paper briefly discusses the Moored Profiler project at WHOI and presents a representative sample of open ocean data. Sections III, IV, and V document the mechanical, electronic, and software features of the MMP. Section VI concludes with some performance data from the ongoing test tank and dockside trials of the MMP.

II. The WHOI Moored Profiler

The WHOI Moored Profiler instrument suite includes a CTD and an acoustic, vector measuring, current meter (ACM). Detailed descriptions of the profiler and sensors can be found in [Doherty, et al., 1999] and [Toole, et al., 1999]. Prototypes of the Moored Profiler, constructed at WHOI, have been deployed in several deep ocean trials over the past 4 years and science experiments utilizing the profilers are now underway. The science applications fall into two general categories. Studies focusing on high frequency motions have acquired profiles rapidly over a relatively short period. For example, a study of internal waves above irregular, sloping bathymetry was carried out in April-May 1998 on the continental slope of the U.S. East Coast. Three Moored Profilers were deployed in a coherent array about the 1200 m isobath and were programmed to synchronously collect temperature, salinity and velocity profiles every 1.5 hours over a 3-week period. Long-term studies are required to elucidate seasonal to inter-annual variability. For example, studies focused on the seasonal formation of water masses by atmospheric cooling are currently underway in the Labrador and Weddell Seas. Profilers deployed there have been programmed to acquire, on average, one vertical profile per day during year long deployments.

Most recently, a Moored Profiler was recovered from offshore of Bermuda where it made two profiles per day from July 20 to Nov 6, 1999. The profiler conducted 217 profiles between 50 m and 3500 m depth before exhausting its battery. The total distance traveled was approximately 750,000 m. The recovered data are an extensive set of high-vertical-resolution temperature, salinity and velocity observations. The temperature data were derived with reference to laboratory-determined sensor calibration data. Adjustments to the conductivity calibrations were made using *in situ* observations from a conventional shipboard CTD system at the adjacent Bermuda Atlantic Time Series Station [Michaels and Knap, 1996]. Potential temperature-salinity curves from the beginning, middle and end of the deployment are shown in Figure 1 and demonstrate the quality of the data. The Moored Profiler observations are comparable to those made by the ship. The most striking feature of Figure 1 is the water mass change at intermediate water levels (temperatures between approximately 3C and 10C). This is due to the replacement of salty Mediterranean Water, present at the beginning of the deployment, by fresh Labrador Sea Water as the autonomous data collection progressed.
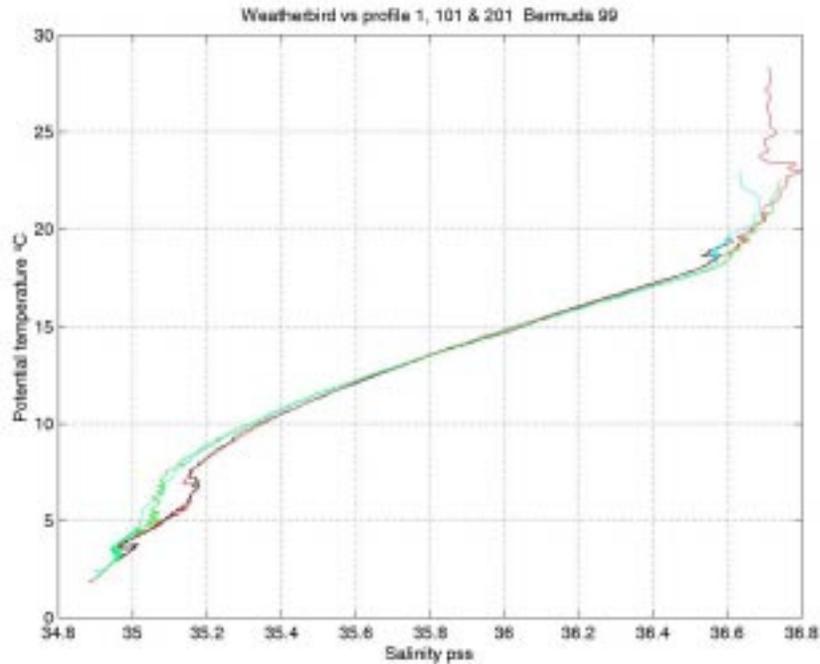
Figure 1- Potential temperature-salinity profiles from offshore Bermuda obtained by a Moored Profiler during the summer and fall of 1999. The first profile and that derived from a shipboard CTD system on the deployment cruise are shown as dark curves. Profiles from the middle and end of the deployment are shown in gray. Note the change in intermediate water (temperatures between approximately 3C and 10C) salinity during the deployment as salty Mediterranean Water present at the beginning of the experiment was replaced by fresh Labrador Sea Water.

The depth-time contour plots of Figure 2 are constructed from the Moored Profiler's long time-series of profiles and resolve the time-history of this water mass change. The transition from Mediterranean to Labrador Sea waters appears to occur around day 25 of the deployment. The companion velocity data are shown in Figure 3. Large vertical-scale currents in excess of 20 cm/s were observed, varying on a 30-to-50-day time scale. Their vertical structure appears to be a mix of barotropic (velocity constant with depth) and baroclinic (velocity varying with depth) motions. Superimposed on these low frequency flows were shorter-vertical-scale, higher-frequency internal wave motions. Ongoing research will investigate the relationships between the internal wave characteristics, the low-frequency flows, the water mass changes, and the atmospheric forcing.

III. Mechanical Design of the MMP

Side and top views of the McLane Moored Profiler are shown in Figure 4. The major components of the system are labeled in the figure. These include the controller, the buoyancy elements, the drive motor and guide wheels, the instrument suite, the internal frame, and the hydrodynamically faired external shell. The platform is designed to profile between pressure limits (or physical stops), powered along a conventional, plastic jacketed mooring cable by a traction drive. While profiling it samples the water column with a suite of instruments and stores the measurements for later retrieval by investigators.

Potential Temperature
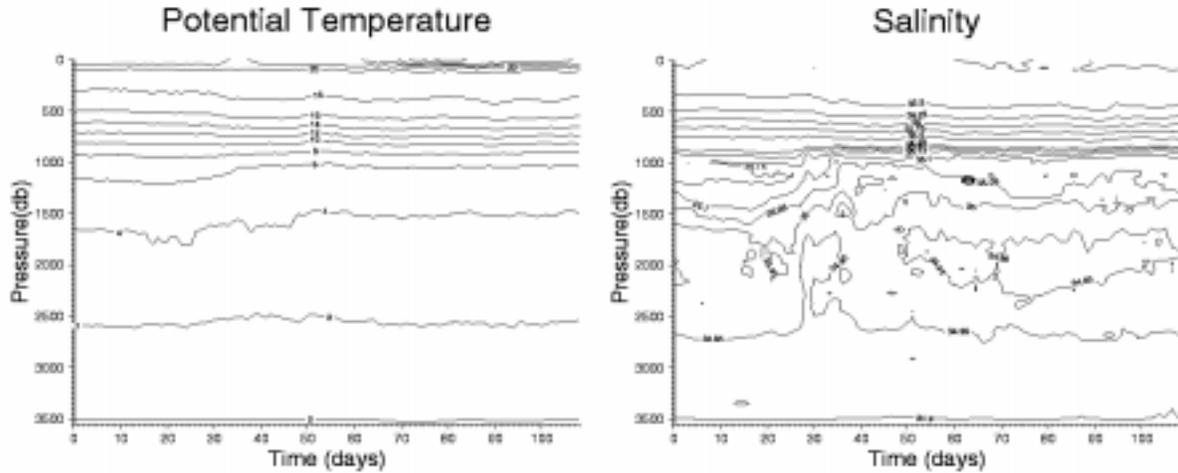
Salinity

Figure 2 - Depth-time contour plots of potential temperature and salinity from the summer-fall 1999 Moored Profiler deployment. The twice-daily 2-dbar gridded data were binned in 20-dbar and 1-day blocks prior to contouring. Note the change in intermediate-depth water mass around day 25 and 1000 dbar. This is associated with the shift from saltier Mediterranean Water to fresher Labrador Sea Water.

East/West Velocity

North/South Velocity
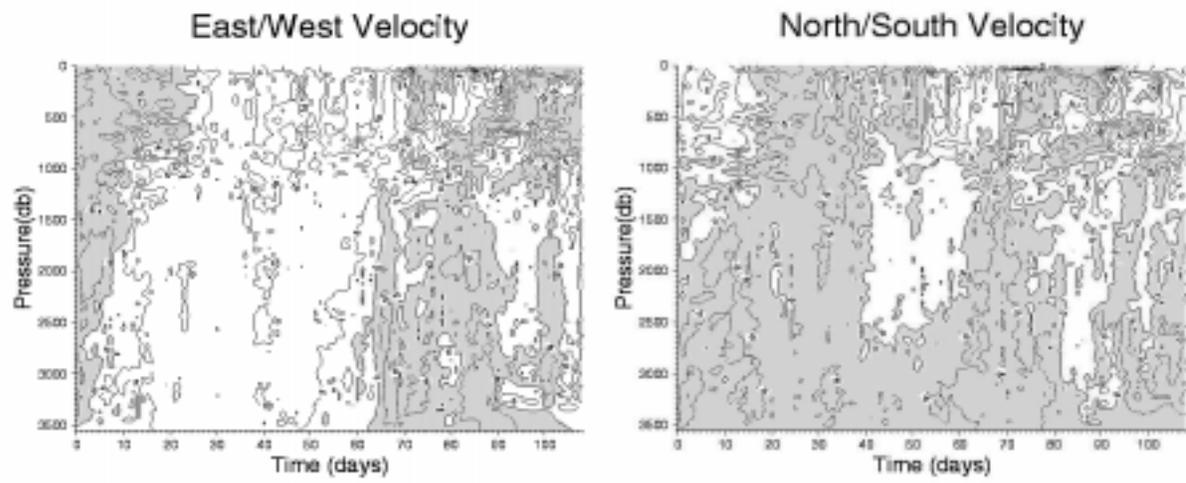
Figure 3 – Depth-time contour plots of the east and north components of velocity from the summer-fall 1999 Moored Profiler deployment. The contour interval is 5 cm/s and regions of negative velocity are shaded. The binning scheme described in Figure 2 was also used here.

The shape and construction of the MMP reflect a balance between several guiding design principles. Low hydrodynamic drag is essential for the vehicle to be capable of million meter deployments. Further, the anticipated combination of vertical motion and horizontal current requires low drag over a broad range of angles of attack. The importance of a low vertical component of drag is clear. The horizontal component of drag increases rolling friction by increasing bearing stress in the motor and guide wheel assemblies. Obviously, bearings appropriate to long-term ocean deployment are also important.

The vehicle must orient itself to face into horizontal currents, even weak ones, as it profiles, so that the instruments sample undisturbed flow. Once oriented, the vehicle must not oscillate or exhibit other complex motions due to vortex shedding or other processes

while profiling. Complex vehicle motions greatly complicate the interpretation of velocity data in particular.

Based on experience with the WHOI Moored Profiler, the design replaces the glass instrument and battery housings with a cylindrical, titanium pressure case. Metal housings can survive rougher handling, can be repeatedly and easily opened and resealed without high risk of damage or flooding, and can be reliably and successfully used by operators who lack the training and experience necessary for success using glass spheres. Access for operation and maintenance, particularly common procedures such as battery replacement and communication for bench testing, deployment, and data recovery, is simple and quick. Finally, the design conforms to the cost and repeatability constraints imposed by commercial manufacturing.

The egg-shaped cross-section, faired end caps, and smooth external shell of the MMP give the vehicle low hydrodynamic drag and profiling stability. At the same time the shape accommodates a cylindrical housing that has sufficient length for batteries and electronics and a 6000 m depth rating. Two glass spheres are used for buoyancy only; they require no user servicing. The mooring cable is located forward of the leading edge of the vehicle to promote the desired orientation of the sensors into the undisturbed horizontal flow.

Figure 4 – Cut away side and top views of the MMP showing the major components of the system. The overall dimensions of the faired external shell are 124 cm × 51 cm × 34 cm.

Visual observations by divers during dockside trials in a tidal current and an analysis of the ACM data have given a preliminary indication that the MMP aligns into the flow and is stable in flight.

The mooring cable threads through faired retainers at the top and bottom of the vehicle. The retainers, which confine the MMP to the cable, can be opened for launch and recovery and are strong enough to support the full weight, including trapped water, of the MMP on a horizontal cable, a normal situation during recovery. The cross-sectional area of the retainer openings is 17.6 cm^2, large enough to allow passage of bio-fouling or other obstructions on the cable. Open ocean trials of WHOI Profilers, which use a similar arrangement of retainers with a traction drive, have not to date been troubled by bio-fouling.

Guide wheels for the cable are located near each retainer. The wheels are machined from

Acetron NS® (DSM Engineering Plastic Products), a solid, lubricant-filled, acetal based plastic which has excellent wear properties. The surface in contact with the cable is, in cross-section, a recessed half circle with a radius of 2 cm. The guide wheels rotate freely on bearing races with Torlon® (Amoco Performance Products) balls to reduce rolling friction.

The drive motor and drive wheel are mounted on a hinge with two degrees of freedom to permit the wheel to pass over obstructions on the cable. The drive assembly is pulled laterally against the cable by a spring, squeezing the cable between the drive wheel and the guide wheels. The cable is under a minimum of 600 pounds of tension. The contact surface of the drive wheel is a recessed 'V' with a rounded bottom. The radius of the bottom is approximately that of the cable. The base of the contact surface is coated with urethane because of favorable wear properties and to increase the level of torque that can be applied by the motor without slip. At the base of the 'V' the radius of the wheel is 2.8 cm. The force of the spring and the shapes of the recessed cross-sections act to center the cable on the drive and guide wheels. The rotational axes of the motor and drive wheel are parallel to avoid unnecessary drive train losses. The guide wheel axes have the same orientation to minimize along axis bearing stress and frictional loss.

The drive train is composed of a precious metal brush DC motor manufactured by Maxon Precision Motor with a 46:1 reduction gear head manufactured by Gysin AG. The motor and gear head run in air inside a titanium pressure housing and are coupled to the drive wheel through concentric, rare-earth magnets. At the nominal voltage of the lithium battery pack, 10.8 V, the along-cable speed of the MMP is approximately 25 cm/s.

This speed is a compromise between energy efficiency and the need to avoid sample aliasing at tidal frequencies. Consider a simplified expression for E_P, the energy required to conduct a single profile.

$$E_P = \left[\frac{F_D}{e} \cdot w \cdot t_P \right] + \left[H \cdot t_P \right]$$

F_D is the hydrodynamic drag force, e is the efficiency of the drive train, and w is the profiling speed. These terms have been combined to express the power that must be supplied to move the vehicle. H is the "hotel load", the (constant) power required by the controller and the instrument suite.[1] It follows that, for a given profile duration, t_P, the terms on the right are the energy required to move the platform and supply the hotel during one profile.

Expanding the terms on the right as functions of the profiling speed yields

$$E_P = \left[\frac{\frac{1}{2} \rho C_D A w^2}{e} \cdot w \cdot \frac{D}{w} \right] + \left[V_B \cdot I_H \cdot \frac{D}{w} \right]$$

where the drag model is quadratic in velocity, D is the length of the profile, V_B is the battery voltage, and I_H is the hotel current. Ignoring the relatively weak dependence of e and C_D (the coefficient of drag) on velocity, it is clear from the form of this expression that there is an optimal profiling speed that minimizes the energy expenditure. Energy efficiency is

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[1] Motor currents that are not related to hydrodynamic drag are considered here to be part of the hotel load. These include the current associated with rolling friction (20 mA to 30 mA) and the no-load current (~25 mA).

reduced at higher speeds because of drag loss and at lower speeds because of the hotel load.

Differentiating with respect to w, equating the result to zero, and rearranging terms yields

$$\frac{F_D}{e} \cdot w_{opt} = \frac{H}{2}$$

The optimal profiling speed is reached when the power required to move the platform is half of the hotel load. The MMP hotel load is approximately 800 mW. Based on an estimate of the motor current associated with rolling friction, measurement of the no-load motor current, and measurements of the total motor current at several profiling speeds, we calculate an optimal profiling speed of ~20 cm/s. This is a little slow for long profiles when tidal periods and other characteristic time scales for ocean change are considered. Increasing the speed will provide sampling relief in trade for reduced mission endurance. A speed of 25 cm/s is consistent with the needs of sampling and still allows the MMP to cover more than a million meters in the course of a deployment.

The internal frame is constructed from ultra high molecular weight (UHMW) polyethylene plastic, which is positively buoyant in water. Additional buoyancy to balance the instrument suite is provided by the two 30 cm sealed glass spheres. Overall, the MMP is positively buoyant and somewhat less compressible than seawater. Lead weights mounted near the base of the frame allow trimming for neutral buoyancy at the middle of the anticipated operational depth range. The front plate of the frame is the primary structural member. Shaped rib plates extend back from the front plate. Secondary members combine to form an open beam, giving the frame its stiffness. The various components of the system are mounted on the front plate and ribs. A skin of UHMW is wrapped around the ribs and secured with recessed edges. Hiding the edges inhibits localized, premature, flow separation that would increase hydrodynamic drag. The faired, hollow end caps, are machined from UHMW. Their external surface was defined using circular and elliptical cross-sections to produce low drag over the expected range of angles of attack. The frame and skin are free flooding.

The baseline MMP instrument suite currently includes the same model CTD and ACM used in the WHOI Moored Profiler. These instruments are products of Falmouth Scientific, Inc (FSI). The CTD was selected for the profilers because of its relatively small size (5 cm diameter, 36 cm length), an anticipated low power (15 mA, 150 mW) version, and the free flushing characteristic of its inductive conductivity cell. The low power version of the CTD is currently in final engineering trials. The ACM was selected for low power (15 mA, 150 mW) and versatility. Both instruments function semi-autonomously during a profile, logging data internally. The data are transferred by the system to non-volatile storage as each profile is completed. The MMP can be equipped with alternate CTDs and ACMs and can also accommodate additional sensors (see Section IV).

A semi-autonomous EdgeTech 12 kHz transponder is mounted near the top of the MMP frame. The transponder allows after launch verification of scheduled profiling using the echo sounder of the research vessel to track the MMP. Elementary communication protocols are also possible, but have not been implemented at this time.

The controller housing is a titanium pressure cylinder with flat end caps and standard double O-ring seals (radial and face). Pressure housings of this type are easily opened, reliably resealed, and require little maintenance. The printed circuit boards of the system's

electronics are mounted on a chassis attached to the lower end cap of the housing. The lithium battery pack that provides power during a deployment is attached to the upper end of the electronics chassis. A pressure relief valve mounted in the lower end cap is included to enhance personnel safety after recovery. Bulkhead connectors on the lower end cap provide ports for the drive motor, CTD, ACM, transponder, and operator communications. The end cap, electronics, and battery can be removed from the housing as a single assembly. Access to the lower end cap and housing requires only the removal of the lower faired end cap. This is accomplished by removing a single recessed bolt and sliding the fairing off of four retaining posts.

IV. MMP Electronics

The MMP controller is a Tattletale® 8 micro-controller manufactured by the Onset Computer Corporation. The TT8 is a compact, high performance, single board computer designed around a Motorola 68332 processor and possesses extensive and versatile digital, analog, and serial I/O capability. Detailed technical information about the TT8 is available through the Onset web site, www.onsetcomp.com.

For non-volatile data storage the controller stack includes a Persistor® AT8 interface board that supports full size ATA style PCMCIA flash cards. The AT8 is a product of Peripheral Issues, Inc. (www.periph.com). ATA cards are currently available with capacities up to 440 Mbyte. The MMP system is designed for a single card, but can potentially accommodate up to three ATA flash cards. The data storage requirement for an MMP equipped with a CTD and an ACM is approximately 220 Mbyte per million meters of travel.[2] The flash cards are MS-DOS compatible and can be read and copied at bus speeds on PCMCIA equipped PCs for data analysis and archiving. This feature makes the data offload operation fast and reliable. There is no need to stream the data off the MMP through the 9600 baud serial port (55 hours for 200 Mbytes). Simply move the flash card to a PCMCIA equipped PC and copy the files to the hard disk or an archival medium (potentially less than 1 minute depending on PC and media).

The third board in the controller stack was designed at MRL. Circuitry on the MMP board (MMPB) includes all of the interfaces between the controller, the operator, the sensor suite, and the profiler platform. Also included are the power distribution network and a watchdog interrupt/reset circuit with an independent real-time clock. System power is provided by a 10.8 V, 240 Ahr lithium battery pack. This is connected to the system through isolation diodes and self-resetting semi-conductor fuses on the MMPB. The combined current drain of the motor, controller, and CTD/ACM instrument suite during a profile is less than 200 mA (at 25 cm/s and using the anticipated low power CTD). Power distribution to the motor, the communications links, and each individual instrument in the sensor suite is switched under the control of the TT8.

The hardware portion of the operator interface is a standard, 3-wire, RS-232 connection on the MMPB. It is compatible with standard PC serial communication ports. The operator

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[2]The anticipated low power CTD produces 9 byte records at 2 Hz. An upgraded ACM produces 18 byte records at the same rate. Time stamps and engineering data for each profile are also stored. The effective data rate is approximately 55 bytes/s. The platform's along cable speed is 25 cm/s or 220 bytes/m. Using the existing CTD and ACM the data rate is approximately 400 bytes/m.

communicates with the MMP through this interface using a PC running a terminal emulation program. The software portion of the operator interface (Section V), which is running on the TT8, allows interactive control of the MMP.

For serial communication with peripherals the MMPB is equipped with two dedicated RS-232 connections for the CTD and the ACM, one auxiliary RS-232 port, two RS-485 ports, and an enhanced SPI (Serial Peripheral Interface) port. The additional ports were included to accommodate expansion or modification of the instrument suite. Complementing the serial ports are five analog channels (with reference voltage and ground) and two frequency counting channels. The latter are also capable of logic level I/O. The analog and frequency inputs are suitable for use with a number of commercially available oceanographic instruments including a varied selection of bio-optical and chemical sensors. Two independent, switched power connections, in addition to the dedicated connections for the CTD and the ACM, are also available. This assortment of supplementary I/O capability permits extensive and flexible growth of the instrument suite, efficient use of power resources, and customized additions that require only harness and software changes.

The logic and power circuit for the drive motor is designed for pulse width modulated (PWM) speed control by the TT8. This is presently used to limit motor current and torque during the start of a profile. Ramping up the speed over a 30 second interval prevents the torque from exceeding the slip limit of the magnetic coupling. Once full speed is reached the modulation is removed to reduce processor overhead and maximize drive train efficiency. Closed loop speed control to meet specialized sampling requirements is possible using the PWM feature, but the total distance traveled during a deployment would be reduced. The drive circuit enables the system to monitor and log motor current. The current through the motor at 25 cm/s is approximately 125 mA, reflecting the power spent to overcome fluid drag and rolling friction. In addition to PWM and steady running, the system can set the motor to free wheel or brake by leaving the motor leads open or shunting them both to ground. In all cases, the components of the drive circuit are protected by hardware from back EMFs generated in the motor by relative motions of the mooring cable. Excessive motor currents while running are detected by the software and trigger status dependent behaviors. These include iterative attempts to pass through perceived obstacles on the mooring cable, a possible cause of high motor currents.

It is axiomatic that transient, unforeseen conditions can disable an instrument without causing permanent damage. One occurrence that is not uncommon is micro-controller lockup caused by pathological cases not considered in software, spurious signals on I/O, data, or address lines, or glitches on a power bus. While fault tolerance is designed into the MMP at many levels, system failure without physical damage is an explicitly acknowledged possibility. For this reason a watchdog circuit is included on the MMPB. The watchdog is nominally powered by the main battery pack, but has a short term (approximately 10 day), independent supply for immunity to transient power supply interruptions. The watchdog sends a periodic interrupt signal to the TT8. If the interrupt is not acknowledged within a specified interval, the watchdog sends a master clear signal, resetting the TT8. This restarts the operating program. In the absence of operator input during initialization, the program loads operational parameters from a file on the flash card and proceeds with the deployment. That parameter file is updated each time an operator programs a deployment.

The remaining two circuit boards in the controller housing are dedicated to operation of the semi-autonomous transponder. Links to the controller stack include only power and two logic lines. One of the lines signals the controller each time the transponder transmits and the other allows the controller to command a ping.

V. MMP Software

The operating software for the MMP is written in C. The software is a mix of user interface and internal/autonomous code that gives the operator great flexibility in planning and carrying out a deployment and extensive diagnostic and testing capabilities.

The internal code is comprised of the low level operations that schedule events, control the drive motor, maintain communications channels to sensors, manage data acquisition and logging, monitor system status, and perform the many other tasks on which operation depends. By design, autonomous operation is fault tolerant and only a very short list of conditions (e.g., a critically low battery level) will cause premature termination of a deployment. All other fault conditions are addressed in ways that do not preclude at least partial completion of the planned experiment. For example, if a mooring cable obstruction is detected based on unchanging pressure data, the MMP will maneuver several times to pass the obstacle. Failing that, it will complete its present profile within the obstruction-constrained, limits. The next profile set will occur as scheduled and the system will attempt to carry out the set using the originally programmed parameters, encountering the obstruction anew if it is still present. All of this activity is logged in the data files for use in data analysis after the MMP is recovered. In general, the system monitors and proactively checks for error conditions so that they can be addressed before they lead to system failures. Trying again rather than terminating a deployment always holds the possibility of success or partial success. Given the importance and expense attached to any long-term ocean deployment and the certainty that unanticipated conditions will be encountered, autonomous shutdown should, as a general or default response, be avoided. This same general philosophy led to the inclusion of the watchdog circuit, described in the previous section, and the critical fault handler, which commands a reset from software when the processor internally detects problems such as memory violations or illegal instructions.

The operator interface is a straightforward tree structure with a main menu and several branching layers of submenus. Communication requires only a PC with a serial port and a terminal emulator. The Main Menu is shown at the top of the next page.

Option 1, Set Time, is used to set the independent real-time clocks (RTC) of the TT8 and the watchdog circuit. The Set Time utility is typically used to set the RTCs to local time or to a standard reference such as UT. The TT8 RTC is the reference for all event scheduling during a deployment. The watchdog RTC runs independently after operator initialization and is used to correct the TT8 clock only in the event of a watchdog restart.

The Flash Card Ops submenu gives the operator access to the flash card where data and system files from a deployment are stored. A subset of basic DOS commands can be used. Several of these are coded into the submenu for single keystroke access. These include commands to size and format the file space, list files, view the profile count, and hot swap cards. Other instructions from the command set can be entered manually. The cards are formatted for compatibility with DOS and can be read on any PCMCIA equipped PC.

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           McLane Research Laboratories, USA
                McLane Moored Profiler
           Version: mmp-1_06.c   S/N: 16268


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      ║              Main Menu               ║
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            Mon Jan  3 14:05:49 2000


      <1> Set Time          <5> Bench Test
      <2> Flash Card Ops     <6> Deploy Profiler
      <3> Diagnostics        <7> Offload Deployment Data
      <4> Sleep              <8> Contacting McLane

         Selection  ?
```
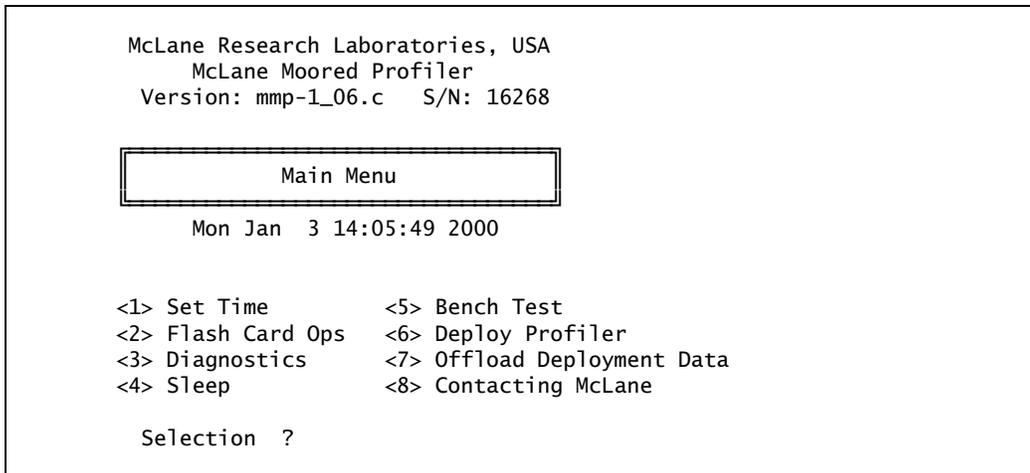
The Diagnostics option scrolls time tagged measurements of battery voltage and motor current to the screen, permitting the operator to check the battery without opening the end cap of the controller housing. Valid voltage and current readings also verify proper operation of the analog-to-digital converter and the SPI port.

Selecting Option 4, Sleep, puts the TT8 in its lowest power mode. Its current drain during sleep is less than 450 µA. Sleep is entered automatically if an operator does not respond to a prompt within 20 minutes. Sleep mode is also entered between events during deployments. The TT8 wakes-up based on alarm times or when interrupted by the operator. The watchdog and transponder interrupts are still serviced during sleep.

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      ╔══════════════════════════════════════╗
      ║             Bench Tests              ║
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            Tue Jan  4 12:37:09 2000

      <1> CTD Communications
      <2> ACM Communications
      <3> Motor Operation
      <4> Brake set.  Change?
      <5> Ping Transponder
      <6> Get CTD Pressure
      <7> Get CTD Average Pressure
      <8> Display ACM Tilt and Compass
      <M> Main Menu

         Selection  ?
```
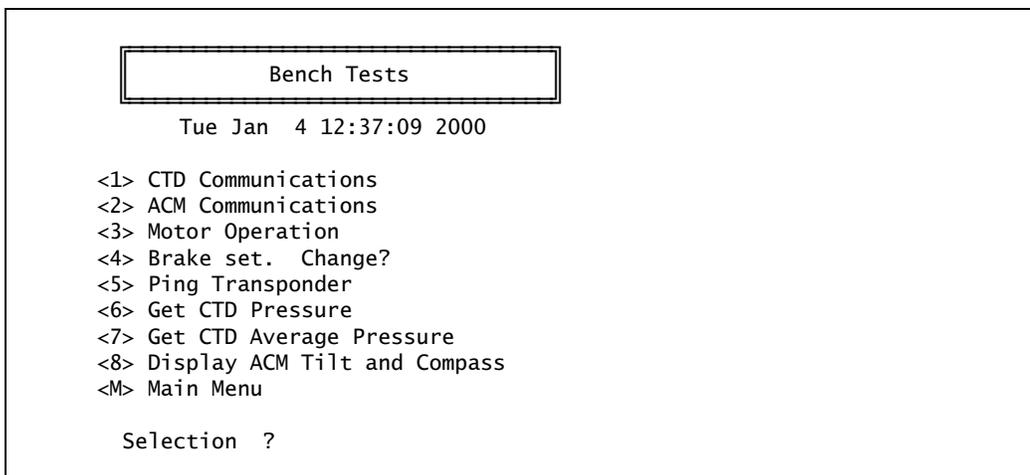
The Bench Test submenu is shown above. From this point the operator is able to exercise and test all of the peripheral devices of the MMP while on the bench or on deck preparing for a deployment. Options 1 and 2 give the operator pass-through access to the primary instruments in the sensor suite. Pass-through access is equivalent to a direct connection between the sensors and the PC, allowing the operator full access to the native command set of the instruments. New menu items can be created to support additional instruments. Option 3 tests the operation of the drive motor and Option 4 is a handling

utility that toggles the motor between the free wheel and brake conditions. To facilitate testing, calibration, and other deployment preparations, the menu also includes single datum and scrolling displays of sensor output (Options 5 to 8).

When Main Menu Option 6, Deploy Profiler, is selected the system prompts the operator to set the RTC and offers options for automatically or manually initializing the instruments in the sensor suite and verifying their readiness to collect data. The interactive deployment menu is then displayed. It is from this screen that the operator tailors the parameters of a deployment to fit the needs of a particular experiment. A sample is shown below.

```
Schedule 1| Deployment delay    = 06:00:00  [HH:MM:SS]
         2| Profiles start on      Integer  hours
         3| Start interval      =        8  [hours]
         4| Reference hour      =        0  [hours]
         5| Paired profiles        Enabled

Stops    6| Shallow pressure    =     50.0  [dbar]
         7| Deep pressure       =   2500.0  [dbar]
         8| Shallow error       =     50.0  [dbar]
         9| Deep error          =     20.0  [dbar]
         A| Profile time limit  = 02:45:00  [HH:MM:SS]
         B| Stop check interval =       15  [sec]

         S| System Interface

         D| Done

           Selection  ? d
```

The example settings indicate that 6 hours have been allotted to deploy the MMP and its mooring from the time the operator commits the system to a deployment. Paired up-down profiles will be conducted each day beginning at 00:00, 08:00, and 16:00. The profiles will nominally range between 2500 dbars and 50 dbars and be limited to 2 hours and 45 minutes duration. The Shallow and Deep Errors are depth windows to account for mooring uncertainties and dynamic motions that change the depths of physical stops on the mooring. The system is set to check for pressure stops every 15 seconds. The system also calculates the time rate of change of pressure and a number of other parameters during each check. These state variables are used to trigger various system behaviors, most typically stopping at the end of a profile. Many of these system parameters as well as a number of event time tags are dynamically logged on the flash card in an engineering data file. One such file is associated with each profile. Elements of the instrument suite, under the control of the TT8, log data internally during each profile. At the end of a profile the TT8 transfers the data to the flash card, creating one file from each instrument for each profile.

The MMP is currently restricted to paired or single profile patterns that cover some fixed excursion length on the mooring cable. More complex patterns are possible and an interface similar to a spreadsheet is being designed. Once this is in place an operator will be able to schedule sampling bursts or more complex patterns. For example, an MMP might be programmed to begin a pattern every 12 hours. The pattern could begin with a profile from 3000 dbars to 10 dbars (3.3 hrs). This could be followed by two down-up profile pairs through surface waters (10 dbars to 200 dbars, 0.9 hrs), a down-up pair to 500 dbars (1.1

hrs), two more surface water pairs (0.9 hrs), and a return to 3000 dbars (3.3 hrs) to complete the pattern (elapsed time 9.5 hrs). The pattern definition interface will permit the inclusion of stationary periods for instrument calibration and drift estimation. The MMP would behave like a conventional current meter in these cases.

Main Menu Option 7, Offload Deployment Data, allows the operator to view selected portions of deployment data files through the primary serial communications port. An example is shown in Section VI. Data are displayed on screen and can be downloaded in ASCII text format using the file capture capability of the terminal emulator. However, this is not the preferred method for downloading the complete data set. Characters are transferred through the communications port at only 9600 baud, far too slowly to read the contents of a 440 Mbyte flash card in any reasonable period of time. The offload utility exists so that selected deployment data can be examined before opening the controller housing. The feature is also useful during bench trials. As noted previously, high-speed offload is achieved by transferring the flash card to a PC and copying the files at bus speeds.

The final Main Menu option, Contacting McLane, simply displays contact information and the revision number of the operating code.

VI. Performance Tests

Operational testing of the MMP has, to date, largely been conducted in the MRL test tank (15 m depth) and off the WHOI dock (22 m depth). The data presented here are from a trial conducted off of the WHOI dock on June 28, 1999. A jacketed cable, fitted with a weight to produce tension and a bumper to protect and support the profiler during launch and recovery, was suspended from a crane and positioned approximately 10 m from the end of the dock. Before being removed from the water the profiler completed 50 profiles between depths of approximately 4 m and 17 m.[3] The system recorded an additional 23 profiles on the dock before operation was halted by the operator.

Divers followed the MMP through several profiling cycles and made visual observations of the response of the vehicle to weak and moderate horizontal currents (5 cm/s to 20 cm/s). At the stops and during each profile the MMP consistently aligned into the flow and returned to alignment when perturbed by a diver. The along-cable velocity was smooth and regular. No oscillations, such as might be induced by vortex shedding, were observed while the vehicle was in flight. However, a brief episode of irregular oscillation occurred during a programmed pause at the bottom stop. This may have been caused by vortices shed from the MMP, perhaps during a transitory burst of stronger current. The vehicle has not yet been tested in a strong, sustained current. It is worth noting that, while undesirable, oscillation at the stops does not presage oscillation during a profile. The WHOI Moored Profiler oscillates in some currents when stationary but is stable in flight. We believe this occurs because the profiling vehicle moves away from shed vortices before they can affect it. Alternatively, the single observed oscillation may have been due to a passing vortex shed from one of the dock pilings. The WHOI dock rests on a number of 1 m diameter pilings. Tidal currents flowing under the dock generate vortices that had compromised observations of vehicle stability during an earlier trial in the dock's test well. We had positioned the

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[3] The pressure limits were actually set through the operator interface to 9 dbar and 22 dbar to allow for the absolute offset of the 6000 dbar CTD being used during the trial. The presented pressure data is in this range.

cable 10 m off of the end of the dock for this trial in an effort to avoid this complication, but occasional interference remains a possibility. While testing has not been completed, we are confident, based on these observations and an analysis of the ACM compass and velocity data, that the vehicle provides a stable, well oriented platform for the instrument suite.

The system creates an engineering data file on the flash card at the beginning of each profile. Time tags and status information are written to the file as events occur and the file is closed once the profile is complete. The engineering file from profile 17 of the June 28, 1999 dock tests is shown below in its entirety. This is the format in which the information is displayed on a PC by the MMP offload utility. Profile 17 was chosen at random.

```
Opening file E0000017.dat,
engineering data for profile 17 of 72.

Sensors were turned on at  06/28/99  12:47:05
Vehicle began profiling at 06/28/99  12:48:47

  Date      Time         [s]      [mA]    [V]

06/28/99  12:48:47   930574127      6    11.3
06/28/99  12:48:50   930574130     93    11.1
06/28/99  12:48:53   930574133    149    11.0
06/28/99  12:48:56   930574136    215    10.9
06/28/99  12:48:59   930574139    285    10.7
06/28/99  12:49:02   930574142    306    10.7
06/28/99  12:49:05   930574145    305    10.7
06/28/99  12:49:08   930574148    299    10.7
06/28/99  12:49:11   930574151    294    10.7
06/28/99  12:49:14   930574154    338    10.6
06/28/99  12:49:17   930574157    299    10.7
06/28/99  12:49:17   930574157    295    10.7
06/28/99  12:49:20   930574160    259    10.7
06/28/99  12:49:23   930574163    274    10.7
06/28/99  12:49:26   930574166    245    10.8
06/28/99  12:49:29   930574169    261    10.7
06/28/99  12:49:32   930574172    271    10.7
06/28/99  12:49:35   930574175    215    10.8
06/28/99  12:49:38   930574178    212    10.8
06/28/99  12:49:41   930574181    239    10.7

Ramp exit:     SMOOTH RUNNING
Profile exit:  TOP PRESSURE

Vehicle motion stopped at 06/28/99  12:49:42
Sensor logging stopped at 06/28/99  12:49:44
```

The instrument suite start and stop times contained in the engineering file are used to synchronize sensor records which are not individually time tagged. Vehicle motion start and stop times are also stored and used in post-processing of the sensor data. The exit conditions listed near the bottom of the file indicate system status when behavioral transitions were made. In this case the vehicle was running smoothly when it completed the 30 second ramp (acceleration) phase of the trajectory and began profiling at a steady speed. Profiling ended when the shallow pressure criterion was satisfied during this upward profile. If some obstacle had been encountered mid-cable, this would have been indicated by time

tagged diagnostic messages and engineering data for each attempt to overcome the obstacle.

The bulk of the data are a time history of motor current and battery voltage. The time tags include a redundant column of reference seconds. A column of integers such as this is often easier to load into a plotting program than the formatted time tags on the left. Note the initial voltage drawdown and eventual stabilization evident in the record of battery voltage. The dock trial was conducted using a low capacity, alkaline battery pack rather than the high capacity, lithium battery pack described earlier. The voltage drawdown is typical of alkaline batteries under load. Motor current peaks at nearly 340 mA at the end of the 30 second ramp phase and then settles under 220 mA as a constant wake and steady conditions are established. A braking transient is responsible for the elevated final reading of 240 mA.

The drive motor gear head used during this trial gave the MMP a steady profiling speed of 36 cm/s. The steady current drain of approximately 220 mA, well above the 125 mA estimated for 25 cm/s travel, was caused by the larger hydrodynamic drag of the higher speed. We estimate that 20 mA to 30 mA of the total motor current is associated with rolling friction. The no-load current accounts for an additional 25 mA. The balance of the motor current is associated with hydrodynamic drag. A simple energy balance, assuming constant drive train efficiency and coefficient of drag, indicates that the drag related current drain is proportional to the cube of velocity. By calculation, the total motor current drain at 25 cm/s will be less than 125 mA. This is near the optimal speed for the MMP and gives the system a calculated endurance of 1.2 million meters. A more detailed discussion can be found in Section III.

At the beginning of each profile the system initializes the instrument suite and commands the sensors to log data internally. The instruments log for two minutes before motion starts to allow self-heating transients to subside and to provide sensor bias and drift data for use during post-processing. In current revisions of the software, two minutes of stationary logging is also scheduled at the terminus of the profile to collect additional bias and drift data. However, that feature was not implemented at the time of this trial. When the schedule is complete, the system halts autonomous logging, creates a log file on the flash card for each instrument, and transfers the data to the files. Roughly synchronous portions of the CTD and ACM files from profile 17 are shown below.

```
Opening file C0000017.dat,
CTD data for profile 17 of 72.

 mmho/cm   Celsius    dbars
. . .
+44.3268  +20.9234  +022.079
+44.3356  +20.9209  +021.999
+44.3366  +20.9190  +020.857
+44.3349  +20.9188  +020.723
. . .
+44.3377  +20.9457  +009.313
+44.3239  +20.9449  +008.890
+44.3284  +20.9331  +009.480
+44.3270  +20.9298  +008.948

End of file mark reached for file C0000017.dat
```

```
Opening file A0000017.dat,
ACM data for profile 17 of 72.

  TX      TY       HX       HY       HZ      VPAB     VPCD     VPEF     VPGH
. . .
+12.68  +00.24  +0.1939  +0.8457  -0.4972  -000.42  -006.44  +004.59  -000.95
+12.72  +00.26  +0.1935  +0.8447  -0.4990  -001.30  -006.85  +004.67  +000.32
+12.75  +00.33  +0.1791  +0.8451  -0.5038  -001.85  -007.23  +004.92  +000.25
+12.71  +00.30  +0.1682  +0.8421  -0.5124  -001.65  -007.16  +005.10  +000.88
. . .
+12.49  +00.31  -0.3524  +0.6898  -0.6324  -000.74  -007.00  +000.14  +016.04
+12.52  +00.34  -0.3568  +0.6893  -0.6305  -001.43  -007.61  +001.05  +016.07
+12.45  +00.31  -0.3742  +0.6860  -0.6240  -000.09  -009.29  -000.32  +016.30
+12.39  +00.36  -0.3719  +0.6845  -0.6270  +002.10  -010.86  -002.76  +014.55

End of file mark reached for file A0000017.dat
```

The instrument data are displayed as they would appear on a PC after running the MMP offload utility. The sole difference is that most of the records have been removed for brevity. The displayed data have not been processed and some offsets and other calibration related errors are evident. The first group of records in each display is coincident in time with the end of the two minute sensor warmup period and the beginning of vehicle motion. The second groups include the terminal records from each file. The selection of these particular records from the file was arbitrary.

The CTD records contain raw conductivity, temperature, and pressure measurements. The data have not been adjusted with reference to a calibration standard, however, the conductivity and temperature values are typical for the WHOI dock in June and suggest a well-mixed water column.

The ACM records include x- and y-tilt (degrees), normalized x-, y-, and z-compass readings, and velocity measurements from each of the four acoustic paths (cm/s). The tilt and compass information is used to rotate velocity vectors into a fixed reference frame during post-processing. The 12.5° x-tilt offset indicates an uncorrected rotation of the ACM electronics housing mounted on the MMP frame. The bench testing utilities provided in current revisions of the software facilitate an accurate adjustment by the operator before the MMP is deployed. Changes in the compass values suggest rotation of the horizontal current vector with depth. This is consistent with the observations of the divers. The AB and EF acoustic paths lie in the horizontal plane of the MMP and are oriented at 45° to the horizontal flow when the vehicle is aligned. The CD and GH paths lie in the vertical plane and are oriented at 45° to the profiling direction. Path GH is on the upper side of the sensor head. Corrections for path geometry, gain, offset, wake contamination, and vehicle orientation and motion are required when processing raw velocity measurements. However, the upward motion of the MMP is clearly apparent from the velocity change along path GH.

VII. Directions for Continuing Development

The process documented here sets out for the reader a fairly complete view of the design goals, characteristics, and capabilities of the MMP. The commercial development of moored profiler technology has passed a number of important milestones. However, it

remains an incomplete and ongoing process. At this time we are focused on reliability and endurance testing in the MRL tank, at the WHOI dock, and in the open ocean. Software that will allow the programming of more complex profile patterns is also an immediate priority.

All of our important design goals have been met. The MMP provides a well-behaved, stable platform for the instrument suite and mission endurance exceeds one million meters. The system permits flexible deployment scheduling and supports system and sensor suite diagnostic and testing procedures. By design, the vehicle is equipped to support a variety of additional instruments and features, allowing the application of moored profiler technology to a diverse cross-section of ocean research. Ease of operation and maintenance make the technology accessible to the oceanographic research community as a whole.

Real-time or near real-time telemetry from an MMP mooring is an obvious direction for future development. One possibility we have considered is an inductive communications link from the MMP to the sub-surface mooring buoy with a connecting tether to a surface buoy supporting a data buffer and satellite communication hardware [Frye and Owens, 1991]. In this design the inductive link is implemented using a ferrite core embedded in one of the retainers and a wire wrapped in a loose helix around the top 20 m of the mooring cable. Seawater provides a return path for the wire. This arrangement provides a more robust link than the jacketed mooring cable and a buffer zone to protect the profiler from wave induced motions of the sub-surface buoy.

The WHOI Moored Profiler has demonstrated the viability and utility of moored profiler technology. The McLane Moored Profiler stands poised to make this technology widely available to the oceanographic research community.

Acknowledgements

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