

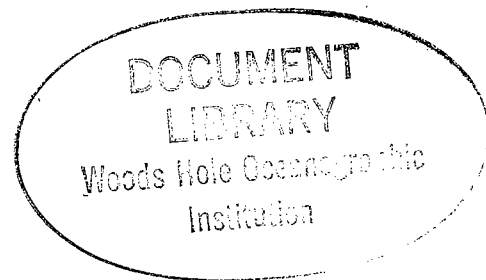
**WHOI-93-33  
UOP Report 93-4**

**The Marine Light – Mixed Layer Experiment  
Cruise and Data Report**

***R/V Endeavor***

**Cruise EN-224, Mooring Deployment, 27 April-1 May 1991  
Cruise EN-227, Mooring Recovery, 5-23 September 1991**

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Paul R. Bouchard  
Andrea L. Oien  
Nancy R. Galbraith



**Upper Ocean Processes Group**  
Woods Hole Oceanographic Institution  
Woods Hole, Massachusetts 02543

May 1993

**Technical Report**

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A handwritten signature in cursive script that reads "James Luyten". The signature is written over a horizontal line.

**James Luyten, Chair**  
Department of Physical Oceanography

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Department of Physical Oceanography



# Abstract

The Marine Light-Mixed Layer experiment took place in the sub-Arctic North Atlantic ocean, approximately 275 miles south of Reykjavik, Iceland. The field program included a central surface mooring to document the temporal evolution of physical, biological and optical properties. The surface mooring was deployed at approximately 59°N, 21°W on 29 April 1991 and recovered on 6 September 1991. The Upper Ocean Processes Group of the Woods Hole Oceanographic Institution was responsible for design, preparation, deployment, and recovery of the mooring. The Group's contribution to the field measurements included four different types of sensors: a meteorological observation package on the surface buoy, a string of 15 temperature sensors along the mooring line, an acoustic Doppler current profiler, and four instruments for measuring mooring tension and accelerations. The observations obtained from the mooring are sufficient to describe the air-sea fluxes and the local physical response to surface forcing. The objective in the analysis phase will be to determine the factors controlling this physical response and to work towards an understanding of the links among physical, biological, and optical processes. This report describes the deployment and recovery of the mooring, the meteorological data, and the subsurface temperature and current data.



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# 1 Introduction

The Marine Light-Mixed Layer (MLML) field program was conceived as a part of the Marine Bioluminescence and Upper Ocean Physics Accelerated Research Initiative sponsored by the Office of Naval Research, and was predicated on the concept that temporal and spatial variability in the marine ecosystem are intimately related to physical processes. The Upper Ocean Processes Group (UOPG) at WHOI took responsibility for the design, deployment, and recovery of an instrumented surface mooring which served as the focal point for the field program. The long-term goal of our work in the MLML program is to develop an improved understanding of upper ocean physical processes and the links among physical, biological, and optical processes. In particular, we are interested in the horizontal and vertical structure of density and velocity in the upper ocean and the response of those fields to heat and momentum fluxes at the sea surface.

From the MLML mooring we have obtained observations sufficient to describe the air-sea fluxes and the local physical response to surface forcing. During the analysis phase, effort will be concentrated on determination of the factors controlling this physical response and consideration of the links between the physical, and bio-optical components of the seasonal cycle in the high-latitude North Atlantic. The primary objectives of this work are: (1) to document the upper ocean response to surface forcing and determine the controlling factors in the restratification and mixed layer deepening processes, (2) to assess the relationship between physical forcing and the bio-optical properties of the water column, in particular the relationship between the onset of restratification and the spring bloom of phytoplankton, and (3) to determine the extent to which bio-optical properties can be predicted given knowledge of the physical forcing and to consider the feedback between physical and bio-optical properties in the development of a mixed layer

model. These objectives will be addressed in close collaboration with the other MLML principal investigators.

In order to understand the link between physical forcing and bio-optical variability we must first know the surface forcing. This forcing consists of wind stress and the sensible, latent, and radiative heat fluxes, which can be computed from the meteorological variables recorded on the mooring using bulk aerodynamic formulae. Given this record of surface forcing, we wish to document the upper ocean response and determine the controlling factors in the restratification and deepening processes. The deep winter mixed layer at the MLML site (Robinson *et al.*, 1979; Levitus, 1982) results from convective mixing due to surface heat loss combined with strong wind forcing. Of particular interest is the spring restratification process, presumably driven by net heating during periods of weak wind forcing. Several studies have been devoted to the seasonal evolution of temperature and current structures in the upper ocean at temperate latitudes (e.g., Briscoe and Weller, 1984, as part of the Long Term Upper Ocean Study experiment, and Dickey *et al.*, 1991, as part of the Biowatt experiment). However, there have been few intensive studies of the springtime transition of the mixed layer and restratification of the upper water column and even fewer comparable observational programs at latitudes higher than 45°N. The temperature and velocity measurements from the MLML mooring document the upper ocean response at a high latitude site with unprecedented vertical (20 m intervals over the upper 300 m) and temporal (1–15 min) resolution.

This report describes the deployment and recovery of the mooring, the meteorological data, and the subsurface temperature and current data.

## 2 Mooring Deployment and Recovery

### 2.1 The MLML Mooring

The MLML experimental site (Figure 1) is in a region characterized by high winds, large waves, and strong currents. This severe environment represented a challenge to our ability to make detailed measurements of local atmospheric forcing and the biological, optical, and physical variability of the upper ocean. The process of meeting this challenge began in 1989 with the design and deployment of the MLML pilot mooring. The pilot mooring remained on station for 10 weeks, after which the failure of a component in the mooring line (a pear-ring link) caused the surface buoy to go adrift and the mooring line to sink to the bottom. The surface buoy was recovered soon afterwards and the sub-surface portion of the mooring was recovered in July of 1990. Analysis of data from the buoy and consideration of the mooring design indicated that both the static tension and cyclic loading on the mooring hardware were higher than anticipated, resulting in the component failure. The 1991 mooring was designed both to minimize the static tension along the mooring line and to survive peak tensions in excess of those observed on the pilot mooring.

Benefiting from extensive evaluation of the performance of the pilot mooring, the 1991 MLML mooring (Figure 2) proved to be a reliable severe-environment platform from which 131 days of surface and sub-surface data were collected between 29 April and 6 September of 1991. The critical design elements of the 1991 mooring included upgraded hardware designed to survive cyclic loading, an increase in scope (the ratio of the slack length of the mooring to the water depth) to minimize static tension, and a compliant element which allowed the mooring to be "tuned" so that the resonant frequency was outside of the surface wave band. The 1991

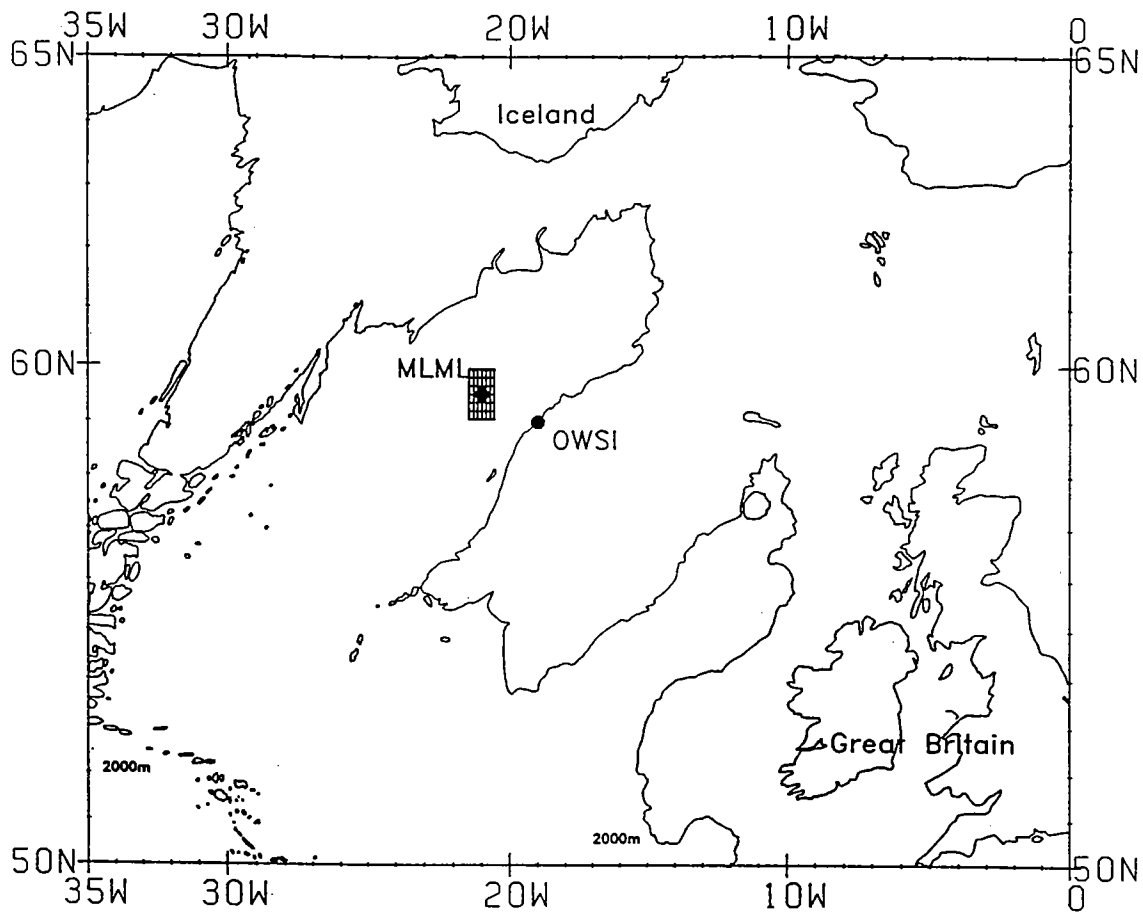


Figure 1: The MLML mooring site at 59.5°N, 21°W is shown along with a grid representing the shipboard survey region. The site at 59°N, 19°W is Ocean Weather Station India (OSWI) where the data of Lambert and Hebenstreit (1985) were collected.

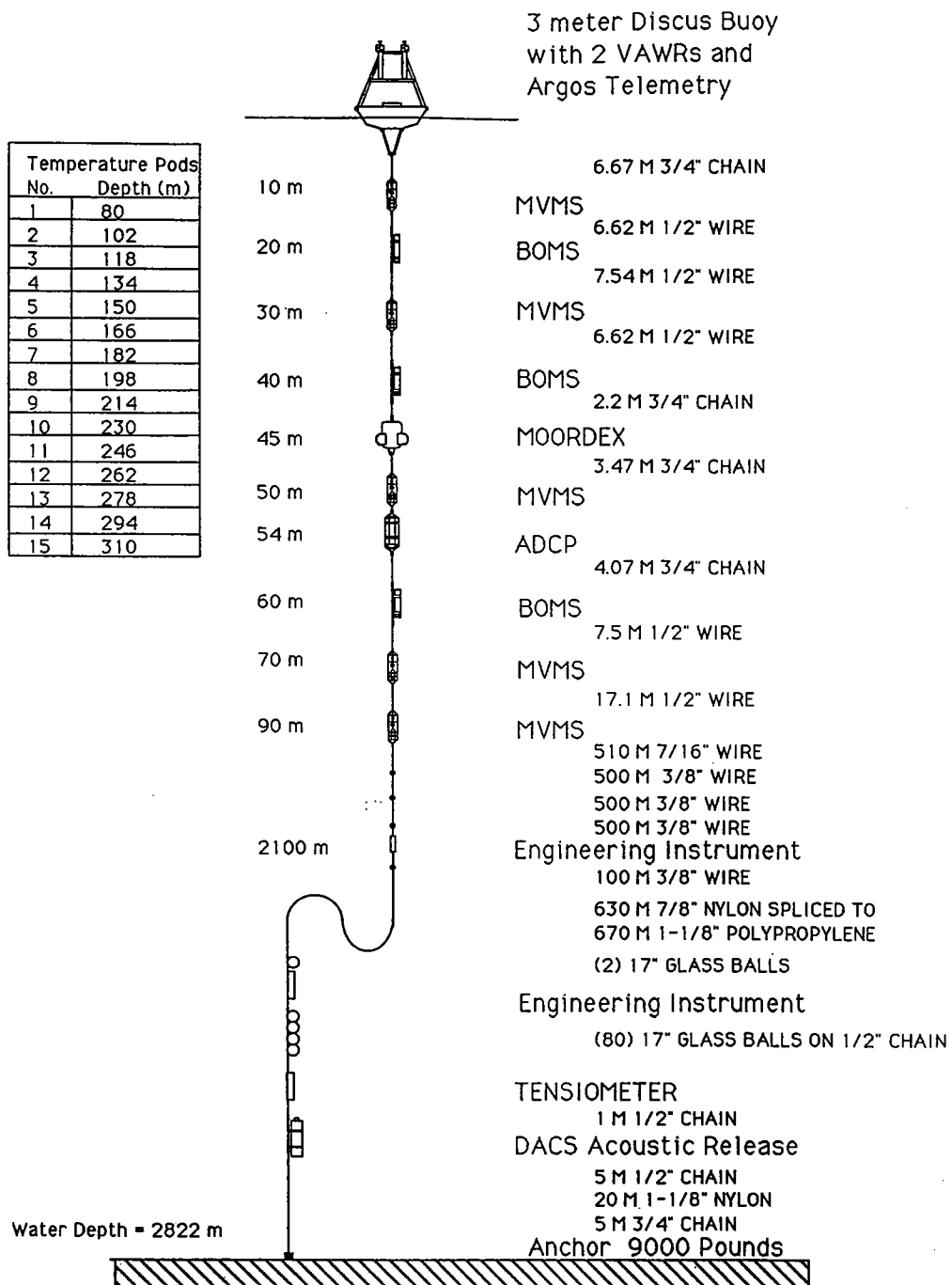


Figure 2: Schematic diagram of the 1991 MLML surface mooring. Instrument acronyms are described in the text.



mooring was of compound (wire, nylon, and polypropylene) construction, using a 10 foot diameter discus as a surface float. The scope of the mooring was 1.25. The mooring used the so-called "inverse catenary" design, wherein a section of negatively buoyant nylon is spliced to a section of positively buoyant polypropylene just above the flotation balls. At low current speeds, the nylon/polypro section takes on an "S" shape (Figure 2). This allows scopes significantly greater than one while eliminating the possible tangling problem of slack line hanging down and fouling lower components in low currents.

## 2.2 Instrumentation

Our responsibility for instrumentation on the mooring included the meteorological measurements and the current and temperature measurements below about 100 m depth. Instrumentation prepared by the UOPG included two Vector Averaging Wind Recorders (VAWR), 15 Submersible Temperature Loggers (STL), an Acoustic Doppler Current Profiler (ADCP), three engineering instruments, and a tensiometer.

Complementary instrumentation in the upper 100 m deployed by other MLML investigators included five Multi-Variable Moored Systems (MVMSs; T. Dickey, University of Southern California (USC) and J. Marra, Lamont-Doherty Geological Observatory (LDGO)), three Bio-Optical Moored Systems (BOMS; R. Smith, University of California, Santa Barbara (UCSB)), and a moored bioluminescence sensor (MOORDEX; J. Case, UCSB). The MVMSs provide point measurements of horizontal velocity and temperature in addition to bio-optical variables, and we include those velocity and temperature measurements in this report. No other data from the USC, LDGO, or UCSB instruments are included.

Instrumentation on the surface buoy included two VAWRs, an engineering instrument for sampling tension and vertical acceleration, a BOMS, and a dissolved oxygen sensor. A communications module was included to allow the VAWR to transmit meteorological data via ARGOS satellite. Two ARGOS antennas were mounted on the buoy tower. Each transmitted data from one of the VAWRs and also provided buoy position data. Another ARGOS transmitter in the buoy well was connected to a flat, deck-mounted antenna. Besides telemetering instantaneous values of buoy tension and battery voltage, this transmitter system was meant to be the backup buoy location device if heavy seas broke off the tower-mounted antennas. An additional backup ARGOS transmitter was mounted on one leg of the three-legged bridle below the buoy. It was mounted upside down and activated by a mercury switch in the event that the mooring broke at or near the bridle and the buoy turned upside down.

Two engineering instruments were placed on the mooring, one at a position 100 meters above the wire/nylon interface and the other just above the glass ball section. They measured tension, inclination, temperature and depth. One chart-recording tensiometer was placed between the glass balls and the release.

One VAWR was scheduled for deployment on the MLML buoy by Marra. To ensure that surface forcing data was collected successfully, we proposed a second VAWR for installation on the buoy. In addition to the ARGOS telemetry, the VAWRs recorded data internally at 15 min intervals. Both VAWRs were outfitted with sensors for the measurement of wind speed (WS), wind direction (WD), sea-surface temperature (SST), air temperature (AT), incoming shortwave radiation (SW), barometric pressure (BP), relative humidity (RH), and incoming longwave radiation (LW). The sensor specifications for the VAWR are given in Table 1.

Parameter	Sensor	Range	Comments
Wind Speed	Gill 3-cup Anemometer R.M. Young Model 12170C 100 cm/rev	0.2-50 m/s	Vector-averaging
Wind Direction	Integral Vane w/ Vane follower WHOI / EG&G	0-360°	Vector-averaging
Short wave Radiation	Pyranometer Eppley Model: 8-48	0-1400 watts/m <sup>2</sup>	Average system
Long wave Radiation	Pyrgeometer Model: PIR	0-700 watts/m <sup>2</sup>	Average system
Relative Humidity	Variable Dielectric Conductor Vaisala Humicap	0-100%	3.5 sec sample
Barometric Pressure	Quartz Crystal Digiquartz Paroscientific Model: 215	0-1034 mb	2.5 sec sample (Burst taken midway through avg. period)
Sea Temperature	Thermistor Thermometrics 4K @ 25° C	-5 to +30°C	1/2 time average Measured during first half of avg. period.
Air Temperature	Thermistor Yellow Springs #44034 5K @ 25°C	-10 to +35° C	1/2 time average Measured during 2nd half of avg. period.

Table 1: Sensor specifications for the Vector Averaging Wind Recorder (VAWR).

<b>sensor</b>	<b>height (m)</b>	<b>separation (m)</b>
SW/LW	3.6	0.1
WS	3.5	1.1
WD	3.2	1.1
AT/RH	2.8	0.2
BP	2.5	0.6
SST (SN 184)	-1.0	-
SST (SN 706)	-2.0	-

Table 2: Height above the buoy waterline is shown for sensors on the two MLML VAWRs. Horizontal separation is given for sensors at the same height on both VAWRs.

All of the VAWR sensors, except SST, were attached to the discus buoy tower. The two SST sensors were attached to the buoy bridle at depths of approximately 1 m and 2 m. The buoy tower was a tripod design, with the distance between legs tapering from about 2.5 m at the buoy deck to 0.6 m at the upper platform (Figure 3).

The two VAWR pressure housings were supported by an intermediate platform at about 1.5 m height, and the sensors were clustered around the upper platform at about 3 m height. Sensor positions with respect to the water line are given in Table 2.

All of the meteorological sensors were calibrated both before and after the experiment and "ground truth" measurements were made prior to deployment and recovery of the buoy. The calibrations are discussed in Section 3 and the chronology of the ground truth testing is given in Appendix 2.

Through the efforts of other MLML investigators, the upper 100 meters of the mooring was instrumented with five MVMSs, three BOMS, and the MOORDEX

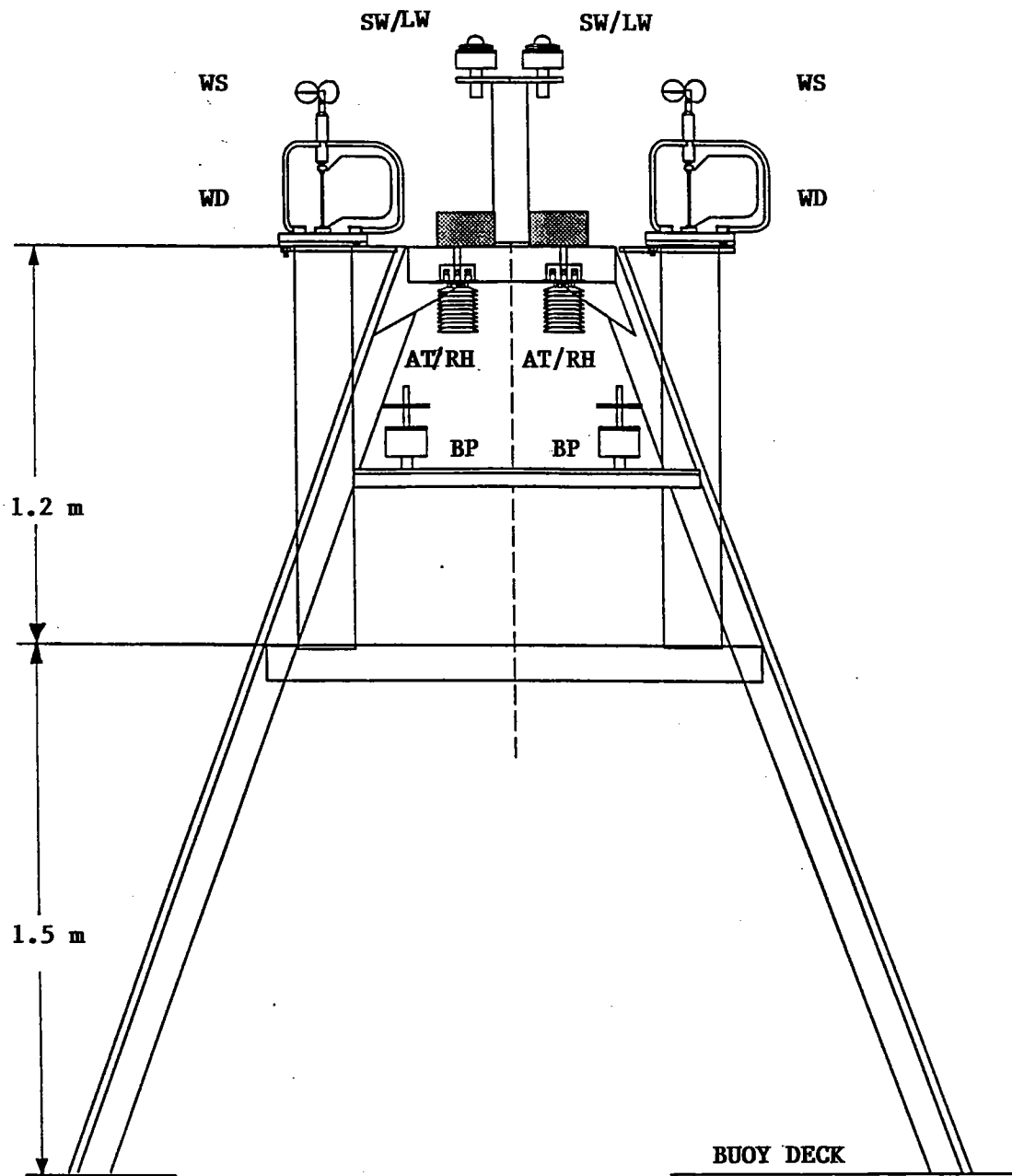


Figure 3: Schematic diagram of the meteorological sensor tower on the 1991 MLML buoy. The buoy deck is approximately 0.4 m above the water line. Sensor acronyms are described in the text.

(Figure 2). The MVMSs were deployed at 10 m, 30 m, 50 m, 70 m and 90 m depth and the BOMS at at 20 m, 40 m and 60 m depth. These instruments provided temperature data at 10 m intervals (except at 80 m) and currents at 20 m intervals between 10 m and 90 m depth. UOPG instrumentation (15 temperature loggers and an ADCP) was deployed to supplement these measurements and extend the range of current and temperature observations to cover the full range of expected mixed layer depths.

The fifteen Submersible Temperature Loggers (STLs) were acquired from Richard Brancker Research Ltd. in Canada. These are self-contained instruments which record internally to solid state memory. Ten of the loggers were Model XL-100 and five were Model XX-105. The two models differ in their temperature precision and pressure case design. The XX-105 has increased precision compared to the XL-100, but over a reduced temperature range. The XL-100 pressure case is rated to 1000 m and uses an externally mounted thermistor, while the XX-105 pressure case is rated to 7500 m and has the thermistor mounted internally. We worked with the manufacturer to modify the XL-100 and XX-105 units to have similar temperature range and precision. For the XL-100, the original YSI 44203 thermistor was replaced by a YSI 44033, resulting in a precision of  $0.012^{\circ}\text{C}$  over a range of  $-5$  to  $30^{\circ}\text{C}$ . The resistors of the XX-105 bridge circuit were chosen to give a nominal precision of  $0.004^{\circ}\text{C}$  over a range of  $3.5$  to  $33^{\circ}\text{C}$  (the actual precision varies slightly with temperature from  $0.002^{\circ}$  at the low end to  $0.007^{\circ}$  at the high end). The stated accuracy of the STLs is  $0.01^{\circ}\text{C}$ . During calibration tests at WHOI we found the XL-100 units met this specification, while the XX-105 units typically performed somewhat better (e.g.  $0.005^{\circ}\text{C}$ ).

The STLs were attached to the mooring wire using a hinge-type clamp which was tightened around the wire. One STL was placed at 80 m depth to continue the 10 m temperature spacing down to 90 m. The remaining 14 sensors were placed at

16 m intervals between 102 m and 310 m depth to match the center points of the averaged ADCP depth cells (see explanation below).

The ADCP was a 150 kHz, self-contained unit manufactured by RD Instruments in San Diego. Outfitted with pendulum tilt sensors, a flux gate compass, and 20 Mbytes of solid state memory, the instrument was clamped to a load cage with the transducers pointing downwards from a depth of 54 m. Four transducers transmitted acoustic energy along narrow beams (approximately 4° half-power beam width) insonifying a volume of fluid determined by the beam width, the duration of the acoustic pulse, and the distance from the transducers. Backscattered energy from the insonified volume arrives at the transducers with a Doppler shift proportional to the average speed of the scatterers in the volume. To the extent that the scatterers are advected with the fluid, Doppler shifts estimated at successive times after transmission provide a profile of water velocity as a function of distance along the beam.

For MLML, the ADCP was configured to send out pulsed transmissions at one second intervals for a period of 60 s. This sequence of 60 transmissions, called an ensemble, was repeated at 15 min intervals. Values of velocity in earth coordinates, echo amplitude, and data quality parameters for each beam, along with heading, tilt, and temperature data were averaged for each ensemble and recorded to memory. The precision of velocity estimates from ADCPs depends principally on the operating frequency and the pulse length. For MLML the estimated precision of the 15 min average horizontal velocities is about 2 cm/s.

The backscattered signal from each transmission is processed over equally spaced time intervals corresponding to successively deeper insonified volumes known as depth cells (the depth cell length is the vertical component of the insonified volume). For MLML, data were processed over time intervals corresponding to a 8 m

depth cell, while the nominal depth resolution of the transmitted pulse was 16 m. Thus, the data were oversampled in depth and successive depth cells are not independent. Forty depth cells were recorded for each transmission, giving a profiling interval of 320 m. The first depth cell recorded was centered at a depth of 66 m and the center of the last cell was at a depth of 378 m. Prior to analysis, the data is usually averaged over two depth cells so that the sampling interval matches the 16 m depth resolution. Considering the two-cell average ADCP data we see that the 102 m STL is at the center of the third averaged cell, the 118 m STL at the center of the fourth averaged cell, etc., down to the 310 m STL which is at the center of the 16th averaged cell.

## 2.3 Deployment

The ship used for the deployment cruise was the R/V ENDEAVOR, operated by the University of Rhode Island, which sailed out of Reykjavik, Iceland for the MLML experiment. The UOPG scientific party arrived in Reykjavik on 22 April 1991 to begin cruise preparations. The ENDEAVOR sailed at mid-day on Saturday, 27 April 1991, arriving at the launch site approximately 275 miles south of Reykjavik at 0420 Z, 29 April. Winds were out of the northeast at 15 gusting to 25 knots. The sea state was 5, with an 8-foot swell, as estimated by the bridge. A CTD was taken to 275 meters at 0500 Z to document pre-deployment vertical structure (Figure 4). The acoustic release lowering was done to 750 meters.

The mooring launch commenced after breakfast on 29 April, with the entire launch operation taking just under eight hours to complete. The anchor went over the side at 1542:30 Z and hit bottom at 1603:52, giving an average descent rate of 132 meters per minute. At the time of anchor launch, GPS was down, so we elected to do the acoustic survey of anchor position using Loran-C. Later, when



C T D No. 2 0500Z 29 APR 91 59° 30' N., 21° 00' W.

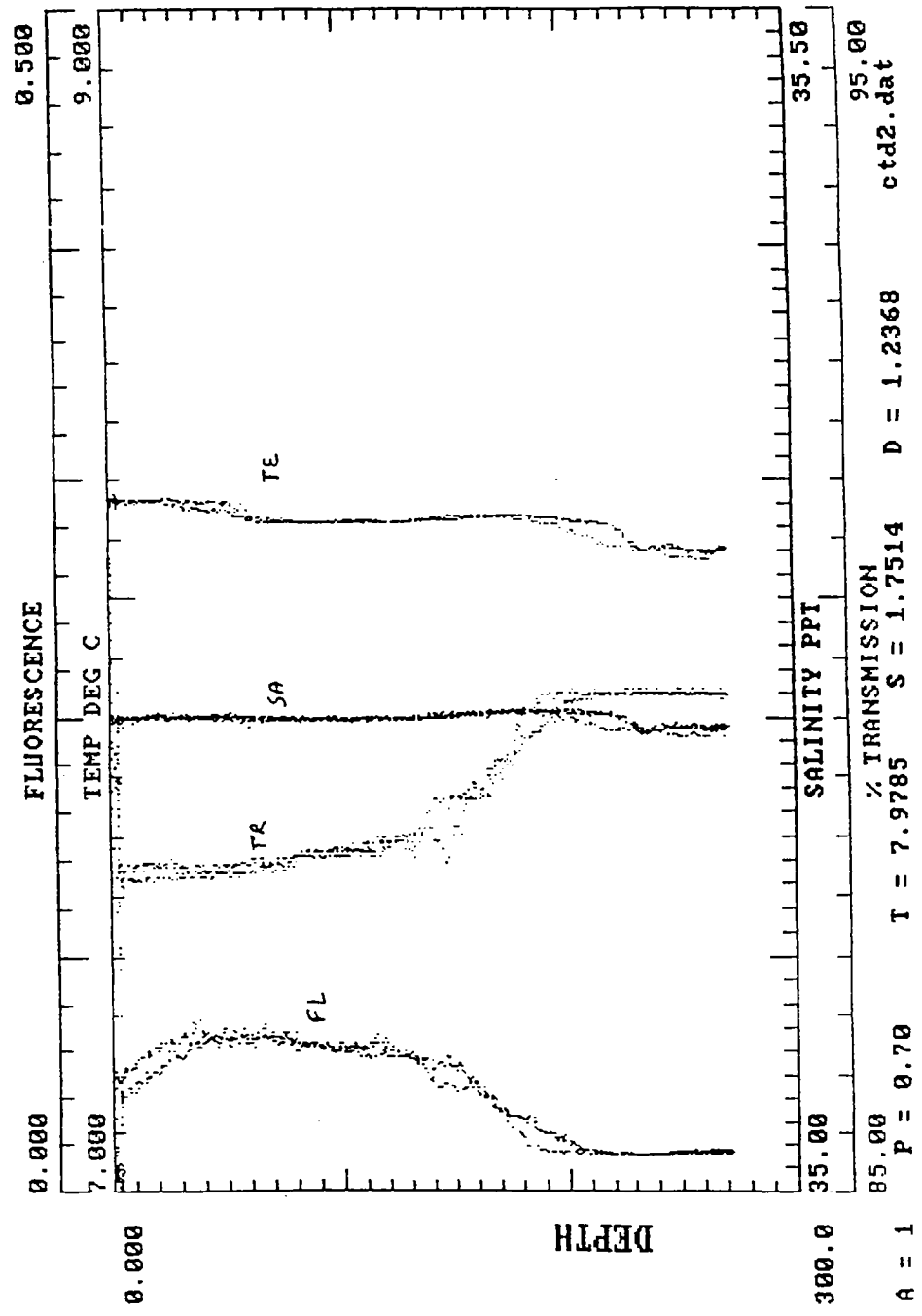


Figure 4: CTD cast taken from R/V ENDEAVOR on 29 April 1992, just prior to deployment of the MLML mooring

GPS was back up, we calculated the offset between GPS and Loran-C. The Loran-C position was 0.44 Nautical miles away and bearing 006° from GPS position. The final position of the anchor was calculated using this offset (Figure 5), giving 59° 35.61'N latitude, 20° 57.85'W longitude. The water depth at the anchor site was determined to be 2822 m. After the anchor survey, the ship approached the surface buoy to log its position and take some video footage. The Buoy position was about 1.2 miles northeast of the anchor.

At 1758 Z on 29 April we launched a Metocean drifter buoy number 14314, given to us by the U. S. Navy (Naval Oceanographic Command) at Keflavik, Iceland. Position of the drifter launch was 59° 34.6'N, 20° 57.2'W. Having completed deployment operations, the ENDEAVOR left the MLML site and returned to Reykjavik on 1 May 1991.

There was interest in documenting the watch circle of the large-scope MLML mooring, which would also aid in determining the safe approach distance to the anchor position for ships working in the area. From the water depth and a scope of 1.25 the horizontal excursion for the buoy is estimated at 2.1 km (1.1 n-mi). However, since the scope is defined using the slack length of the mooring, we must account for the stretch of the synthetic components under load. Assuming that the 1300 m of nylon and polypropylene stretches 15% gives a maximum horizontal excursion to 4.7 km (2.5 n-mi). Buoy positions determined from ARGOS telemetry for the period 1-9 May are shown in Figure 6. These positions have accuracy of about 350 m (0.2 n-mi). The plot shows that the buoy is typically found between the slack-length excursion and the maximum excursion.

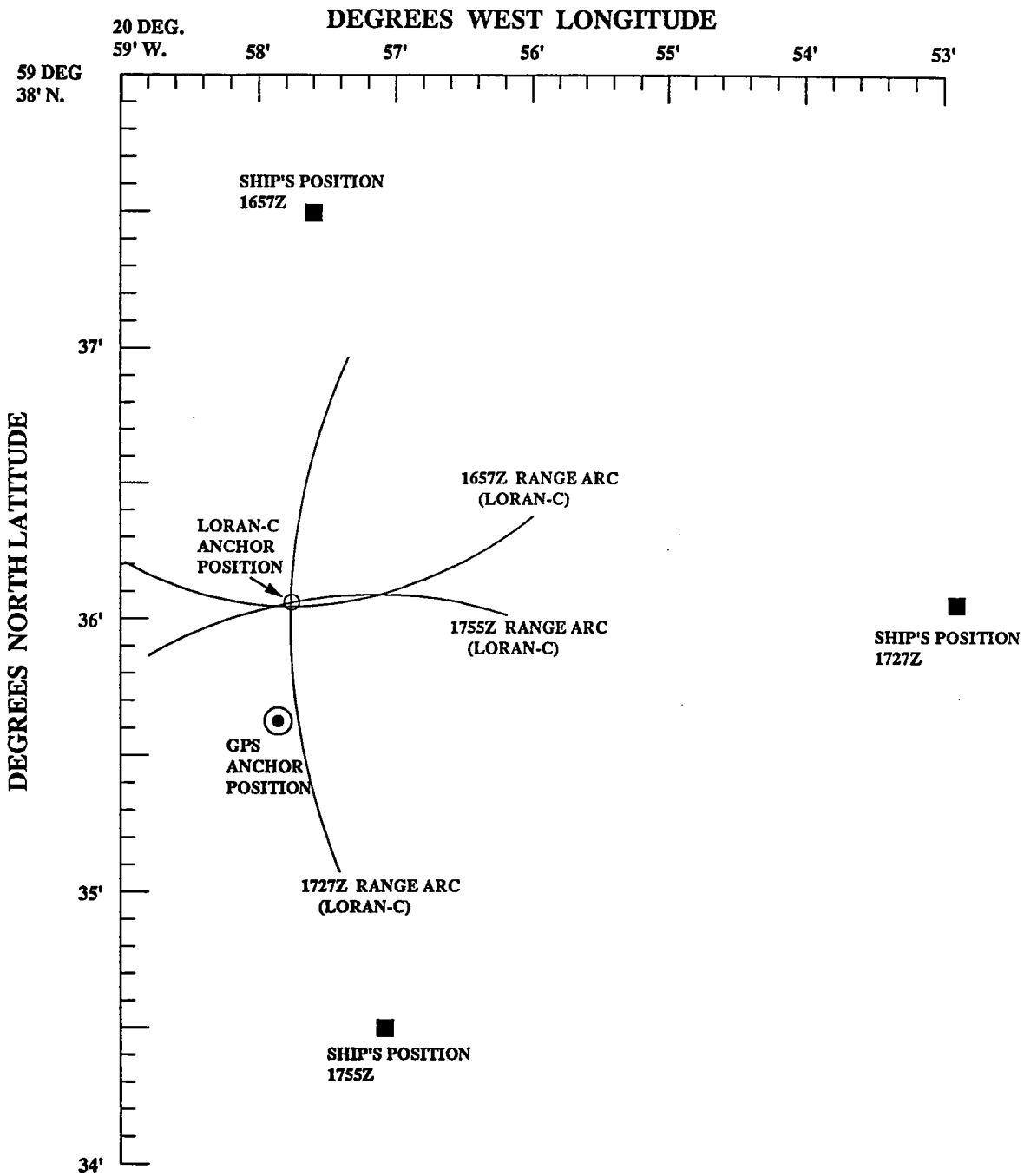


Figure 5: The MLML-91 mooring anchor position, determined from Loran-C fixes while GPS was down, and later adjusted using GPS (see text). The position of the anchor was determined to be 59° 35.61'N, 20° 57.85'W.

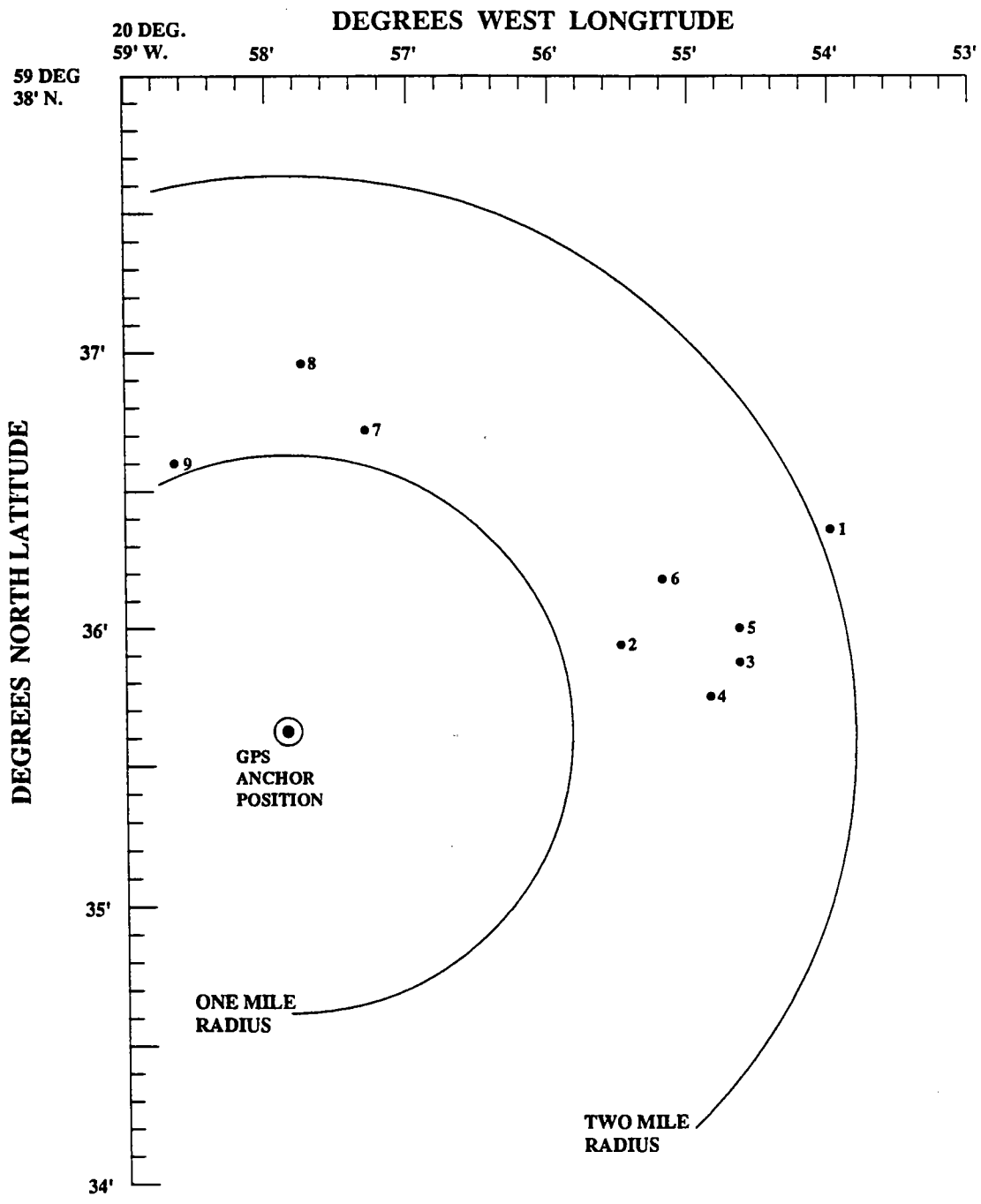


Figure 6: MLML-91 buoy positions from ARGOS for the period 1-9 May relative to the estimated anchor position.

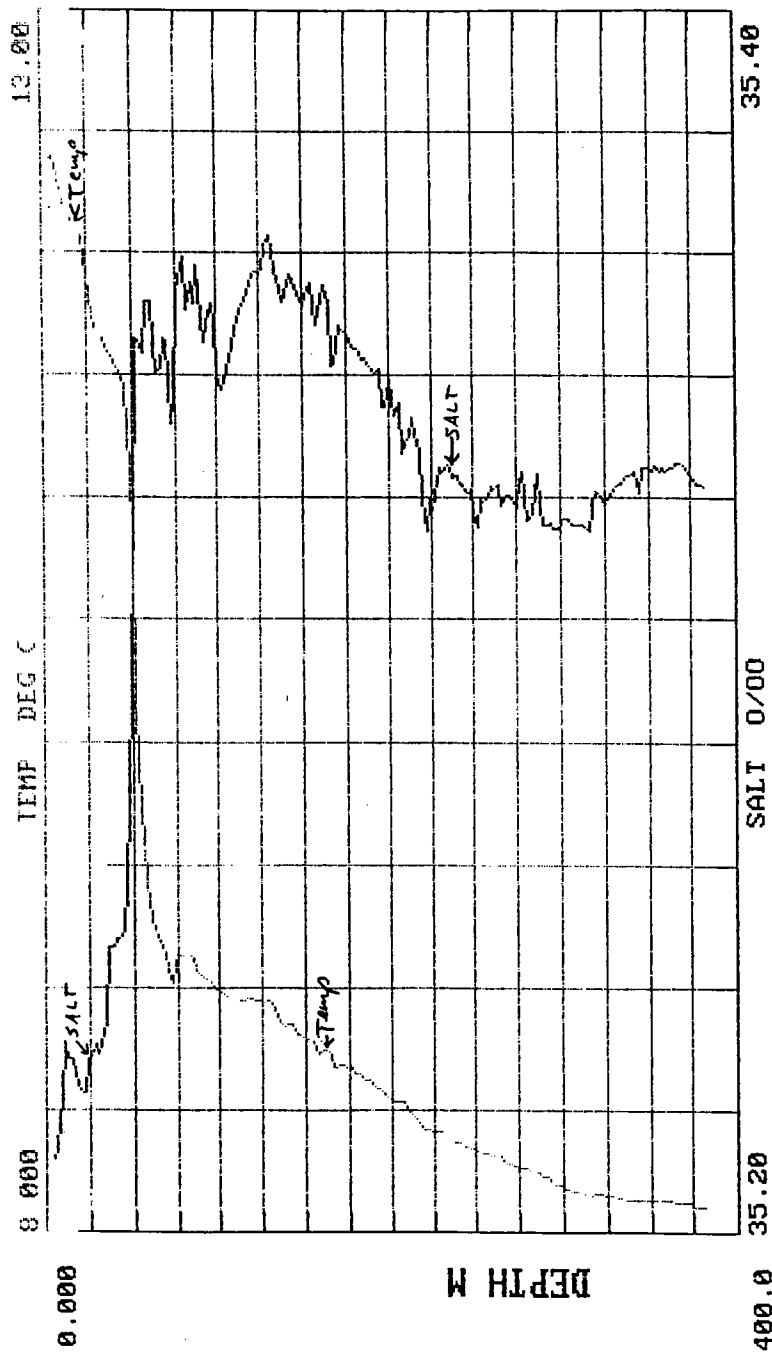
## 2.4 Recovery

The R/V ENDEAVOR sailed from Reykjavik, Iceland for the mooring recovery at 1030 Z, 5 September 1991. The weather forecast called for flat seas for several days, an unusual occurrence at the MLML site, but very good news for the mooring recovery team. A call was made to WHOI just before the ship sailed to check the VAWR ARGOS telemetry data from the mooring, confirming that the highest barometric pressure and lowest wind speeds of the entire experimental record were being observed.

On the morning of 6 September ENDEAVOR arrived at the mooring site. En-route to the mooring in calm seas (sea state 1), the buoy was seen on radar at a distance of six miles. At 1100 Z, the buoy was sighted visually at three miles. The ENDEAVOR hove-to 1/4 mile downwind of the buoy for a half-hour of meteorological ground truth measurements. These data appear in Appendix 2. At least a hundred seagulls were seen around the buoy, mostly swimming, but some perched on the deck with one sitting on top of the BOMS sensor. The deck of the buoy was covered with a greenish algae/weed growth, indicating it had been awash a good bit. Sensors appeared to be undamaged and looked like new. A CTD was taken to 400 meters before the mooring recovery (Figure 7).

The acoustic release was fired at 1250 Z on 6 September and the mooring began its ascent. The recovery went smoothly, with the mooring and all instruments aboard by 1800 Z. Recovery was slowed by the TSE winch not having enough drum capacity to hold all of the mooring; operations had to be stopped midway through to offspool wire so that the rest of the mooring could be hauled in.

The condition of all instruments on recovery was good, with two exceptions. The MVMS at 10 meters was covered with a black, oily fouling. The transmissometer of this instrument was missing, with broken cable hanging loose, and the MVMS



DEN227B.avg: TEMP & SALT AT MLML BUOY

Figure 7: CTD cast taken from R/V ENDEAVOR on 6 September 1992, just prior to recovery of the MLML mooring

at 50 meters had a broken Oxygen probe. The Argos transmitter on the buoy bridle was severely corroded in the mid-section of its pressure case. It was hypothesized that this was due to the lack of a neoprene pad on the bottom mounting bracket base plate, allowing the aluminum case to directly touch the bracket. The mooring hardware and wire rope looked in good shape. None of the STL brackets showed any signs of slippage on the wire rope. The nylon had three small wuzzles all within 100 m of the nylon/polypro splice. The wuzzles may have been caused by the nylon going slack and then throwing a loop and tightening itself on the loop.

The ship left the MLML site after recovery operations were complete, arriving outside Reykjavik harbor early on 8 September. Personnel from LDGO and Mark Grosenbaugh from WHOI departed on the pilot boat, while the rest of the science party remained onboard, sailing south to track down and recover the surface float from the North-West mooring of the Subduction Experiment array which had gone adrift. After recovering the drifting portion of the Subduction mooring on 15 September, ENDEAVOR arrived at WHOI on 23 September, 1992.

### 3 Data Presentation

The surface meteorological variables, air-sea fluxes, upper ocean temperatures, and upper ocean currents observed from the MLML mooring are presented in this section. The observations come primarily from the UOPG instruments on the mooring (two VAWRs, the STLs, and the ADCP), but measurements of currents and temperature from the MVMSs are also included. The principal means of presentation is a series of figures and tables which are described in the text and presented at the end of the section.

#### 3.1 Meteorological Variables

The VAWR data tapes were read for each instrument resulting in files containing time and eight meteorological variables: Wind speed (WS), wind direction (WD), sea-surface temperature (SST), air temperature (AT), incoming shortwave radiation (SW), barometric pressure (BP), relative humidity (RH), and incoming longwave radiation (LW). The longwave radiation measurements from MLML are discussed in Dickey *et al.* (1993) and will not be presented here.

A small number of obviously bad points (less than 0.2% of the samples) were edited out by hand and replaced by linearly interpolated values. In order to eliminate data from periods prior to deployment and after recovery of the mooring, a de-facto definition of MLML-91 start and end dates was made. The resulting files had 12384 15 min samples starting on 4/30/91 00:15 (yearday 120.0052) and ending on 9/05/91 23:45 (yearday 248.9948).

Time series of meteorological variables recorded by the two VAWRs on the MLML mooring are shown in four sections in Figure 8a-d. The data presented are at the 15 min intervals recorded by the instrument, with no additional averaging



variable	mean difference	std dev
WS (m/s)	-0.03 (0.4%)	0.21 (4.8%)
WD (°)	-4.60	3.74
SST_1 (°C)	+0.027	0.050
SST_2 (°C)	-0.036	0.467
AT (°C)	+0.002	0.083
SW (W/m <sup>2</sup> )	-3.15 (1.8%)	5.16 (11%)
BP (mb)	-0.22	0.18
RH (%)	-1.11	0.81

Table 3: Statistics of the difference between measurements of like variables for the two VAWRs are shown. Statistics of the difference expressed as a percent of the two-sensor mean are also shown for some variables. SST\_1 is the period of good performance, SST\_2 the period of bad performance.

applied. Observations from VAWR Serial Number (SN) 184 are shown as a solid line, observations from SN 706 as a dashed line. The extent to which the two lines are indistinguishable is a first-order indication of the quality of the measurements. The only discrepancies discernible in these plots are in the relative humidity and the sea surface temperature.

Time series of the differences (SN 184 – SN 706) between variables observed by the two VAWRs are shown in four sections in Figure 9a–d. These time series, and their statistics (Table 3), allowed evaluation of VAWR performance. The best performing sensor for each variable was chosen to form the “best available” meteorological data from which to compute air–sea fluxes.

Estimates of the accuracy (difference between observed and true value), precision (repeatability of successive readings), and resolution (smallest change detectable by the sensor) for the VAWR are presented by Weller *et al.*, 1990. Values from their Table 3 are quoted in the discussion below. The sensors on the two

VAWRs were in close enough proximity that we expected experiment-long mean differences greater than the sensor accuracy to be indicative of calibration biases. The observed differences at 15 min intervals can be effected by true small-scale spatial variability in the measured quantity. Thus, it would be unlikely that the standard deviation of the differences would be as small as the sensor precision (the precision is the “best case” repeatability under controlled conditions). Still, we expected the standard deviation to be near the estimated sensor accuracy for most variables.

The wind speed difference had a mean of 0.03 m/s and a standard deviation of 0.2 m/s. The standard deviation of the difference expressed in terms of a percent of the wind speed was 5%. The wind direction difference had a mean of 5° and a standard deviation of 4°. This compares with an estimated accuracy of 2% for wind speed and 3° for wind direction. We concluded that the wind sensors were performing within tolerable bounds, although there was probably a small compass calibration bias resulting in the mean difference two degrees larger than the estimated accuracy. From the information available, it was not possible to know which sensor had the larger directional error. Instead we accepted a directional uncertainty of about 5° and chose SN 184 for wind speed and direction based on its more “reasonable” performance during the strong wind event on 20–21 May.

Sea surface temperature was the variable with the most obvious measurement problem. It can be seen from the plots that the difference is small up until about 21 May and after 1 August. During this “good” period, the mean and standard deviation of the difference are 0.03° and 0.05°, respectively. The pre and post deployment calibrations indicated both sensors to be accurate within 0.005° or less, quite reasonable given the estimated accuracy of 0.004°. The observed difference statistics about an order of magnitude larger than the estimated accuracy may be explained by the fact that the two sensors were separated by 1 m in the vertical.

