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Description of an Experimental Investigation on the Response of the Upper Ocean to Variable Winds

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DESCRIPTION OF AN EXPERIMENTAL INVESTIGATION ON THE RESPONSE OF THE UPPER OCEAN TO VARIABLE WINDS

David Halpern

Beginning on 4 August 1971, 32-day time series of currents and temperature in the upper region of the ocean (from about 5 meters to 55 meters) together with time series measurements of surface wind, atmospheric pressure and temperature were obtained at one location in the northeast Pacific, remote from intense boundary currents and from continental boundaries. The primary aim of this research activity was to investigate the response of the upper ocean to variable wind stress.

This report describes the instrumented single-point compound mooring system, the equipment, the testing program and some initial results. It does not contain an analysis of the data.

1. INTRODUCTION

The coupling between the wind, the currents in the mixed layer of the ocean and the currents in the stratified water underlying the mixed layer was investigated at one location in the northeast Pacific for 32.5 days beginning on 4 August 1971. The following parameters were measured from a single-point taut moored surface float: wind speed and direction, atmospheric and subsurface pressures, air and sea surface temperatures, mooring line tension, and in the uppermost 55 meters of the water column, the temperature at 8 locations and the water speed

and direction at 4 depths. Vertical profiles of temperature and salinity to 1500 meters were measured at the start and at the conclusion of the experiment.

The experimental site, which was located at approximately $47^{\circ}03.37'N$, $128^{\circ}17.17'W$, was about 250 km from the continental shelf break and about 220 km from Cobb Seamount of the Juan de Fuca Ridge (Figure 1). This position, which had a water depth of about 2700 meters, was in the central part of the gently sloping Cascadia Basin.

The large-scale oceanographic features of this region have been reviewed by Fleming (1955), Dodimead et al. (1963), Uda (1963) and Tabata (1965). Briefly, these studies indicated that the buoy site was in the Eastern Subarctic Pacific Region or in the transition zone between the Subarctic Pacific Region and the American Coastal Zone. This area is one of excess precipitation (10 cm) between June and August. In summer the high-pressure system (North Pacific High), centered between $30^{\circ}N$ and $40^{\circ}N$, produces surface winds that blow from the northwest. Fofonoff and Tabata (1966) have shown that the mean circulation in the northeast Pacific is in local equilibrium with the mean wind stress. Uda's description of the mean circulation, as deduced from charts of dynamic topography, indicates that the buoy was located in the region of separation of the West Wind Drift where the baroclinic geostrophic currents are weak (4 to 8 cm/sec) and variable in direction.

This particular location was chosen because of the absence of strong permanent-type currents and because it was a deep water region far from bathymetric features that might influence the wind-generated

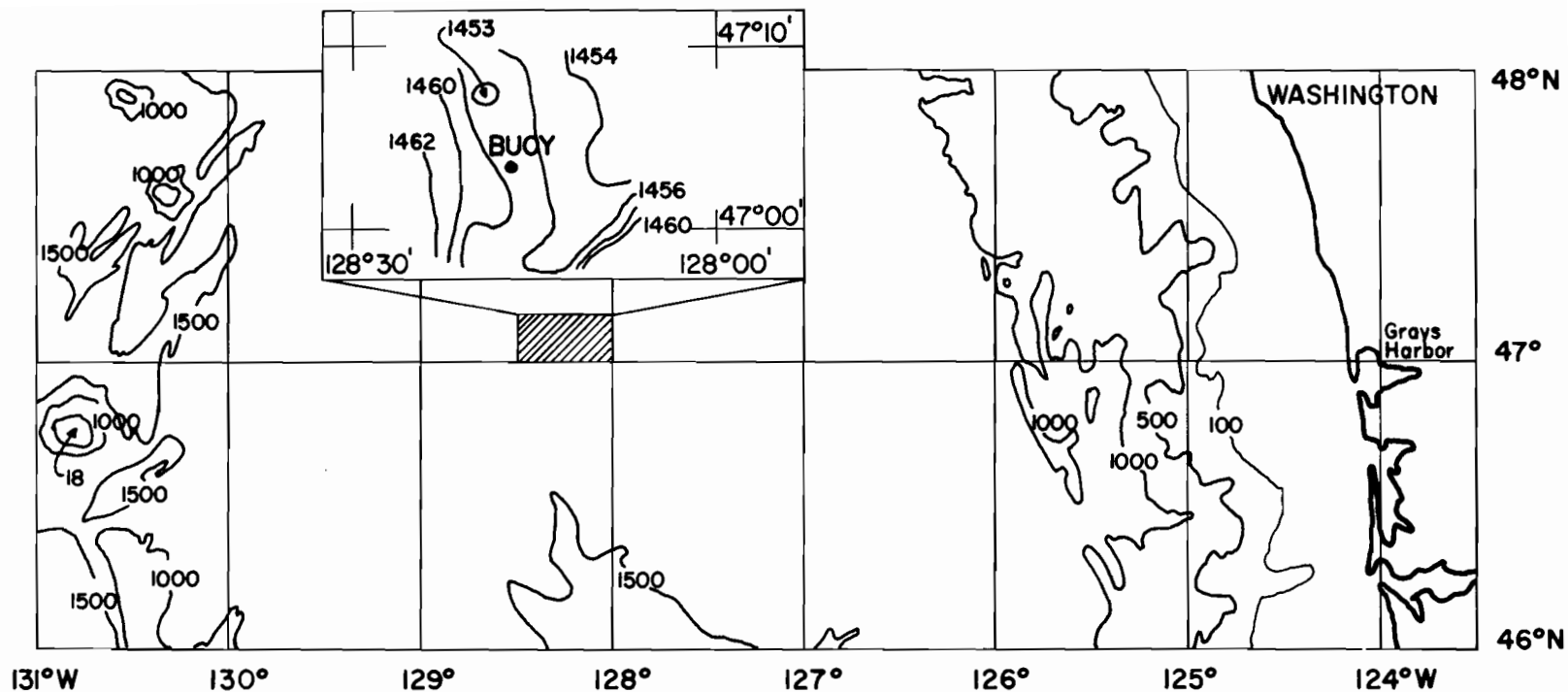


Figure 1. Location of the surface float. Contours in uncorrected fathoms after Carson (1971). Cobb Seamount is located at $46^{\circ}45'N$, $130^{\circ}50'W$. Inset: bathymetry in uncorrected fathoms determined on 3 August 1971.

circulation of the uppermost 100 meters. This area was also far from land so that the wind circulation was not influenced by terrestrial features, yet the buoy station was easily reached from Seattle.

For planning purposes we assumed that the vertical distribution of the water properties of the uppermost 100 meters at the buoy site had the same general features as those occurring at Ocean Station PAPA (50°N, 145°W). According to Dodimead et al. (1963) the isothermal and isohaline layers extend downward to approximately 100 meters depth during the winter and in August a mixed layer extends to about 25 meters depth. Below this layer a summer thermocline, defined by a temperature decrease of approximately 6°C between 25 meters and 50 meters depth, is present to about 75 meters depth. A seasonal halocline provides an additional increase to the stability of the seasonal pycnocline.

2. THE INSTRUMENTED SINGLE POINT TAUT-LINE COMPOUND MOORING

Figures 2 and 3 and Tables 1 and 2 show the positions of the instruments used in the study. The subsurface depths were calculated by summing the lengths of each of the mooring components which are listed in Appendix A. The data lengths recorded by the unattended instruments are given in Tables 1 and 2.

The meteorological instruments consisted of a wind recorder that measured wind speed and direction, an atmospheric pressure recorder and two air temperature and sea surface temperature recorders. By sea surface temperature we mean the water temperature at about 0.4 meters

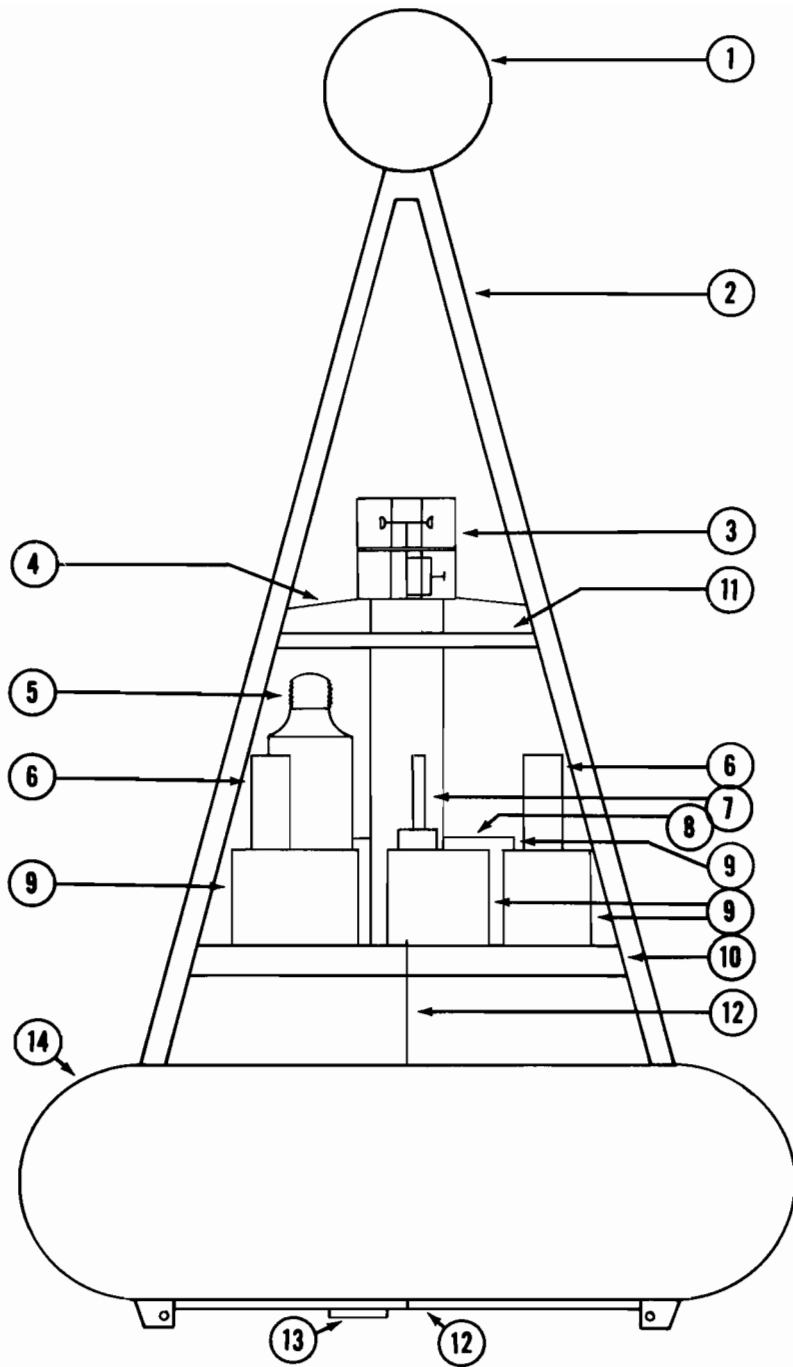


Figure 2. The instrumented surface float. Table 1 is the legend for this figure.

Table 1. Equipment mounted on the surface float and the instrument-record length distribution. The start of the experiment was defined as 0800 GMT 4 August 1971, which was 7 hours 44 minutes after the anchor was released at the sea surface. The end of the experiment occurred at 0800 GMT 5 September 1971, which was 8 hours 25 minutes before the acoustic release was fired to separate the anchor from the mooring cable.

Circled number of Figure 2	Item	Height of Sensor Above Water-line (meters)	Record length (days)
1	Radar reflector	3.5	
2	Aluminum tripod tower		
3	Wind recorder	2.0	32.0
4	Stainless steel guy wires		
5	Buoy light	1.6	
6	Thermistor	1.3	17.7
7	Radar transponder	1.3	
8	Atmospheric pressure recorder	1.0	17.0
9	Boxes containing electronics and batteries for 6, 7, 8 and 13		
10	Aluminum grate platform		
11	Aluminum cross-bar		
12	Stainless steel pipe		
13	Thermistor	-0.4	17.7
14	Toroidal buoy		

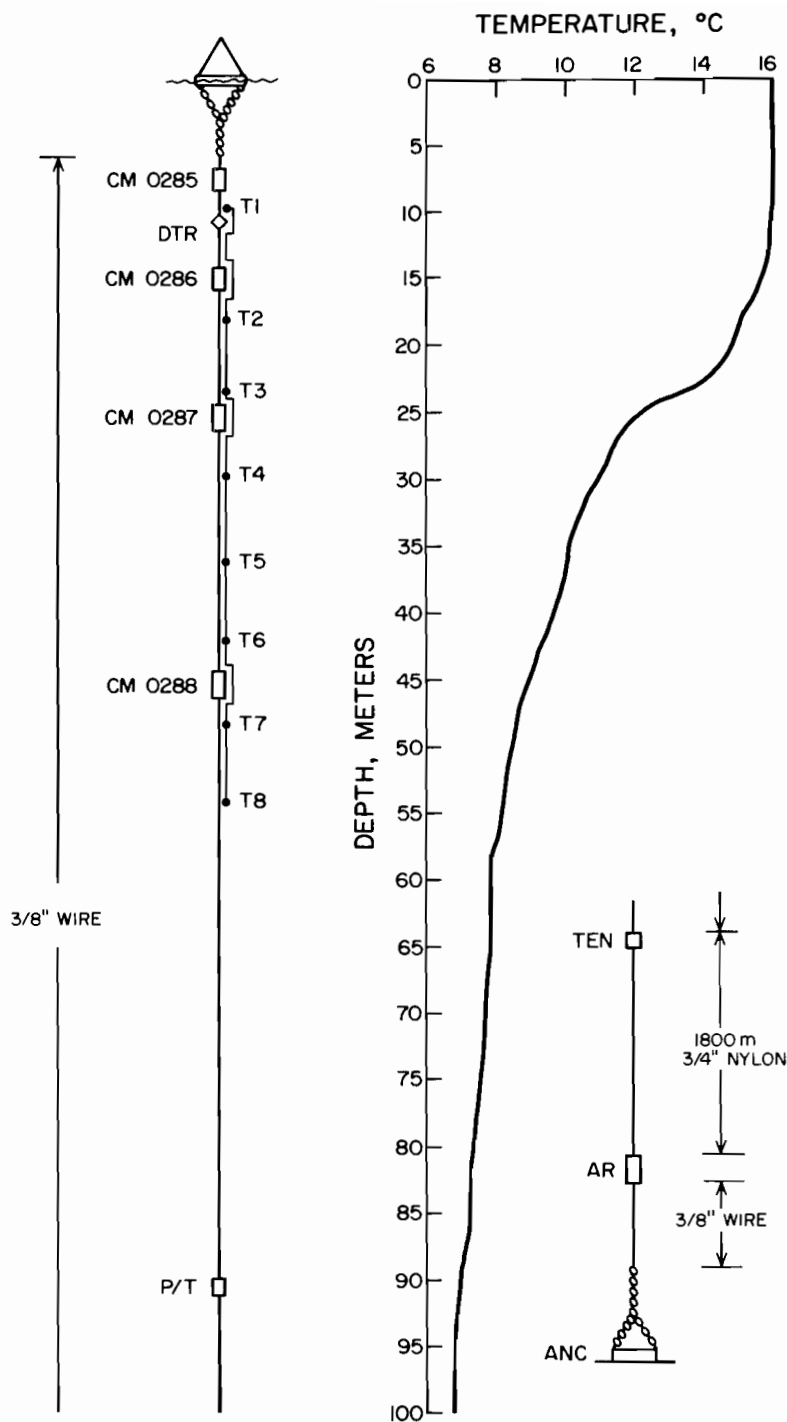


Figure 3. In-line positions of the subsurface instruments and the vertical distribution of temperature measured on 3 August (STD cast 1001) at a location approximately 23 km northeast of the buoy site. CM = current meter, T1...T8 = thermistors, DTR = digital temperature recorder, P/T = pressure and temperature recorder, TEN = tension recorder, AR = acoustic release, and ANC = 4000 pound Stimson anchor.

Table 2. Depths of the subsurface sensors and the instrument-record length distribution. (See Table 1 for definition of record length.) Depth is given for the bottom of the current meter.

Instrument	Depth (meters)	Record length (days)
Current meter 0285	8.3	32.0
Thermistor 1	9.6	31.4
Current meter 0286	15.8	27.2
Thermistor 2	17.6	5.3
Thermistor 3	23.4	31.4
Current meter 0287	26.2	32.0
Thermistor 4	29.8	31.4
Thermistor 5	36.0	31.4
Thermistor 6	42.1	31.4
Current meter 0288	46.2	32.0
Thermistor 7	48.1	31.4
Thermistor 8	54.2	31.4
Pressure and temperature recorder	91.0	32.0
Tension meter	392.3	32.0

below the surface. The air-sea surface temperature difference will be used as an indicator of atmospheric static stability, for it is well known that the drag coefficient occurring in the square law expression for wind stress is dependent upon the gravitational stability of the air.

The experiment was designed so that the uppermost two current meters were placed in the upper isothermal layer (Figure 3) which was virtually coincident with the mixed or isopycnal layer. Current meter 0287 was placed at the top of the seasonal thermocline with the anticipation that by the end of the experiment the thickness of the mixed layer would be greater than 25 meters. The fourth current meter was located near the bottom of the seasonal thermocline. The current meter observations were intended to help describe the wind-induced currents in the mixed surface layer and the circulation in the presence of a seasonal thermocline, and hence the extent of the coupling between the layers. The temperature sensors were intended to measure the thickness of the mixed layer and to provide necessary data to calculate, together with the current meter data, the Richardson number.

To reduce the amplitude of the inevitable mooring motion which produces noisy data we used a single point taut-line compound mooring configuration that consisted of a 390-meter upper and a 246-meter lower section of 9.53 mm diameter torque-balanced 3x19 wire rope manufactured by United States Steel* and an 1800-meter middle section of 19.1 mm

*Reference to specific brands, makes, or models of equipment in this publication is made for identification only and does not imply endorsement by the U. S. Dept. of Commerce.

diameter 8-strand plaited nylon line manufactured by Columbian Rope. To meet the requirement of a taut-line mooring we first made a bathymetric survey of the mooring site (see inset of Figure 1) and water depth was monitored during launch. The water depth at the buoy site was approximately 2700 meters. When wet, the total length of all the mooring components between the surface and the anchor was about 2426 meters. Because the nylon line was measured dry under a tension of approximately 40 pounds, the resultant shrinkage of the 1800-meter length was about 0.6%. Therefore, in the absence of wind, waves and currents, we presumed that the nylon rope would stretch 274 meters or about 15.1% of its length when the anchor rests on the bottom. This amount of stretch corresponds to a line tension equal to about 1450 pounds, which is 11% of the rated breaking strength of the wet nylon (Figure 4).

The tension meter measurements, which record the downward pull occurring at the upper end of the nylon line section, show that the average tension measured during 5 August (when winds were light and variable in direction) was about 450 pounds. Since the combined weight of the mooring line components occurring between the tension meter and the upper end of the triangular chain bridle that was adjacent to the anchor was about 440 pounds (Appendix A), it seems likely that on 5 August, and on many other days, a segment of the 3-meter long chain bridle rested on the bottom. Consequently, the scope of the mooring line was probably equal to 1.0 and not 0.9 as planned. Furthermore, during those intervals of time when the recorded tension was low, i.e., about 500 pounds, it appears that the nylon line was virtually unstressed.

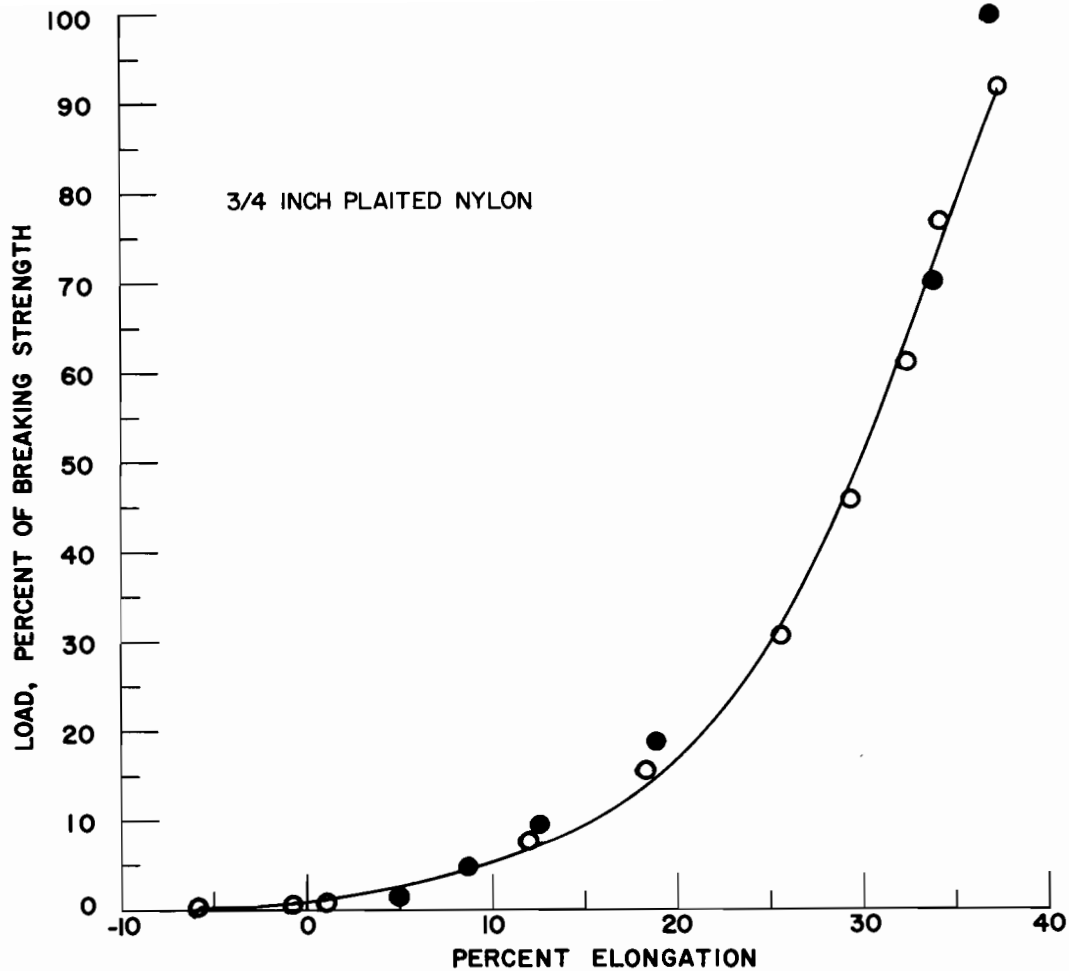


Figure 4. First loading curve (open circles) of wet 3/4 inch (19.1 mm) diameter 8 strand plaited nylon line which had a breaking strength equal to 13,150 pounds. Black dots represent stress-strain measurements made on a piece of line used in the experiment. The breaking strength of this sample was 11,200 pounds. (Data courtesy of Columbian Rope Company.)

The nylon line terminations, each of which consisted of a thimble with an eye splice of 4 tucks, were prepared by the manufacturer. Preventer ears for the thimbles were made with Panduit plastic tie wraps. The wire rope terminations were ESCO duplex swaged fittings prepared by B and J Industrial Supply. The breaking strengths of the following mooring components were tested at the University of Washington's Engineering Materials Laboratory: two 21.6 mm Crosby-Laughlin round pin anchor shackles, a 21.6 mm Crosby-Laughlin weldless sling link, a 1-meter length of 21.6 mm Campbell high test chain and two 1-meter lengths of 9.53 mm wire rope - one with a Nicopress fitting and one with an ESCO fitting. The shackles, link and chain suffered only minor abrasion at 35,000 pounds tension at which point the test was terminated. The wire rope slipped out of the Nicopress fitting at 5800 pounds tension, while the ESCO fitted wire rope broke at the fitting at 14,200 pounds tension, which was 600 pounds less than the rated minimum breaking strength.

The subsurface instruments were self-contained units that were suspended in-line with the mooring cable and were free to rotate about the vertical. Ball-bearing Miller swivels were placed beneath the buoy bridle and at the upper and lower ends of the nylon line section. An arrangement consisting of a shackle, weldless sling link and shackle was generally used at the top and bottom of each instrument and between each shot of nylon line. The link provided a convenient location for stopping-off the mooring cable during deployment and retrieval.

The surface float consisted of a Geodyne Model A-92 toroidal buoy and an aluminum tripod tower that was welded and bolted to three

metal bands wrapped around the toroid. The bottom of each band contained a 25.4 mm diameter eye for securing the float to the mooring line. A platform of aluminum grating was welded to the tower and the tower was further strengthened with welded aluminum cross bars.

3. RECOVERY AND DEPLOYMENT OF THE MOORING

The deep sea mooring was set by a version of the "buoy first, anchor last" method. With the surface float aboard the ship, the top section of the mooring (i.e., the four current meters and the temperature profiling system) was suspended vertically in the water from the stern A-frame. When all was ready, the chain bridle attached to the toroid was shackled to the uppermost current meter. Then the surface float was lifted into the water and floated astern, the mooring cable was paid out over the stern with the ship moving slowly into the wind, the remaining instruments were inserted into the mooring system by stopping-off the cable at the appropriate places, and the 4000 pound Stimson anchor was lowered to the naviface and then released so that it plunged towards the bottom in a free-fall. About 10 to 20 minutes after the anchor was dropped, the surface float moved with a bow wave towards the ship. For about one or two minutes the toroid became virtually submerged. Soon afterwards the toroid surfaced and attained its equilibrium state of submergence.

During the 90 minute interval when the 1800 meter section of nylon line was being paid out there was very little tension in the mooring cable, for a person was easily able to pull the nylon rope

towards the ship. During this interval, and until the anchor completed its unconstrained free-fall, the tension meter measurements (Figure 5) showed low levels of tension, i.e., approximately 50 pounds (22.7 kg). Because the torque-balanced nonrotating wire rope and nylon rope were highly resistant to kinking, unwinding and birdcaging, the risk of permanent rope damage was greatly diminished. When the depth reached by the anchor was such that the mooring cable was approximately straight, the tension meter began to feel the pull of the anchor. According to Berteaux and Walden (1970) the anchor then swings somewhat like a pendulum in a complex path determined by the elongation and drag of the mooring cable and by the motion of the surface buoy. At anchor bottoming the tension reached its maximum value of 3400 pounds (1553 kg)(Figure 5). The time of the pendulum mode was about 17 minutes. During the last phase of the launching transient the buoy, pulled by the restoring force of the stretched nylon line, travelled towards its equilibrium position. Both the length of line and the tension, therefore, decreased.

No problems occurred in either the deployment or in the retrieval of the system. When the acoustic release responded to the "release" command, a Zodiac raft pulled the surface float astern of the ship where it was lifted from the water. Because the top section of the mooring cable appeared to be heavily strained, we used the crane to lift it. However, we are confident that the anchor cable dropped when the acoustic release fired because the tension in the nylon line immediately relaxed to a level approximately equal to the combined wet weights of the acoustic release and of the mooring components occurring below the tension meter (Figure 5).

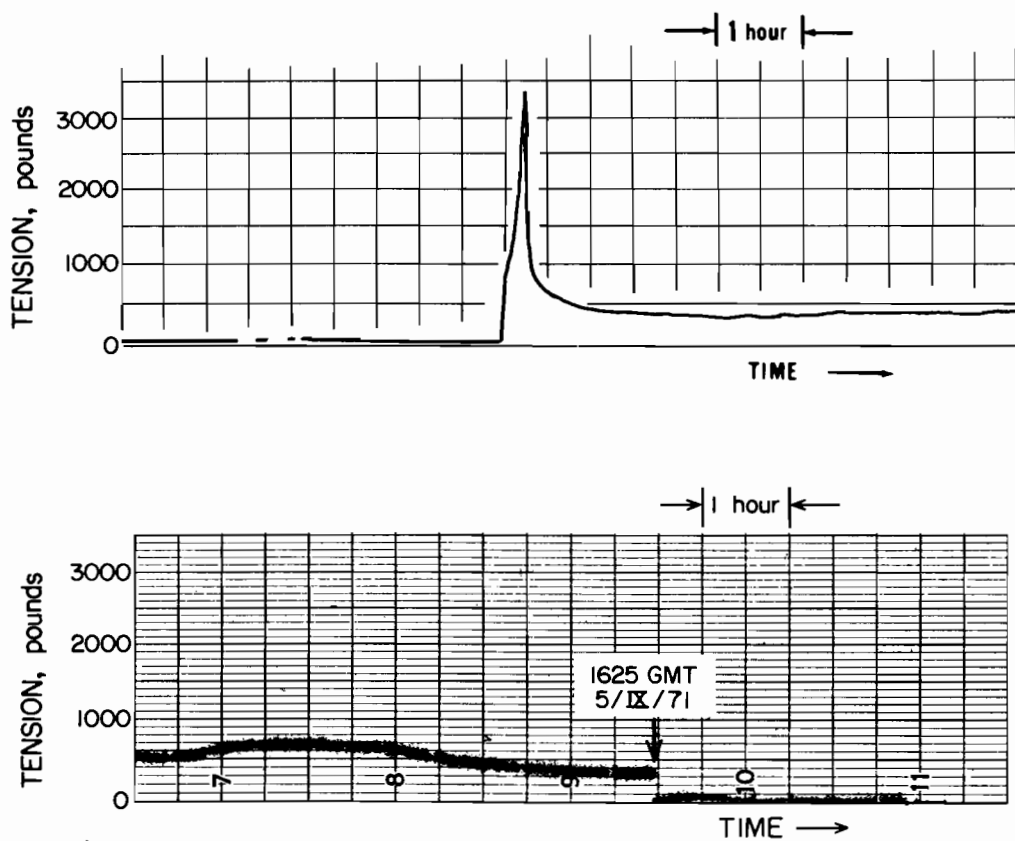


Figure 5. Upper: A re-tracing of the tension record measured during the deployment of the mooring system. Lower: The tension record measured when the anchor was released from the mooring.

4. BRIEF DESCRIPTIONS OF THE INSTRUMENTS

4.1 Current Meter

The Geodyne Model A-850-2 tape recording current meter with digital clock, which is based on a film recording model originally developed by Richardson (Richardson et al., 1963), records current speed and direction. The manufacturer claims that the instrument measures water current speed in the range between 2.6 and 360 cm/sec with an accuracy of ± 2.6 cm/sec for speeds less than 51 cm/sec and twice this for speeds greater than 51 cm/sec. The resolution and threshold of speed measurements determined by the National Oceanographic Instrumentation Center (1971a) were ± 0.47 cm/sec and 4.11 cm/sec, respectively. The rotor time constant (time for 63% response to a step change) measured by Gaul (1963) was nominally 1 second for acceleration and 2.5 seconds for deceleration, both measured above 10.3 cm/sec for a speed change about equal to the mean speed. The manufacturer specified that the rotor rotation rate was equal to 1.60 revolutions per minute per 1.0 cm/sec and that this value was constant between the speeds 26 cm/sec and 256 cm/sec.

The direction of current is measured by the simultaneous recording of the instrument-vane orientation, which gives the direction of the current relative to the instrument, and the magnetic compass reading, which gives the orientation of the instrument relative to magnetic north. Current direction is defined as the direction in which the water is flowing. Two bar magnets mounted on the neutrally buoyant vane sensor

couple the vane movements to the vane follower assembly located inside the case. For a 90° step change in the direction of the vane the vane follower time response is approximately 1.6 seconds (National Oceanographic Instrumentation Center, 1971a). The manufacturer claims that (1) the compass accuracy is $\pm 3^\circ$, (2) the vane accuracy is about $\pm 10^\circ$ for current speeds less than 2.6 cm/sec and about $\pm 2^\circ$ for current speeds greater than 2.6 cm/sec, and (3) the current direction is independent of instrument tilt for vertical tilt angles less than 30°. The current direction resolution was $\pm 2.8^\circ$ (National Oceanographic Instrumentation Center, 1971a), which is the readout resolution of the vane follower electronics assembly.

The data are recorded in binary format on dual-channel 6.4 mm magnetic tape in an endless-loop cartridge. The second channel is switched on after the first one is filled.

Our instruments recorded a burst of six samples every 3.75 minutes and each of the six samples, which consisted of a speed, a compass direction and a vane direction, was measured at 4.95-second intervals. Speed was determined over the 5-second interval by counting the number of reed switch closures produced by 16 small magnets mounted on the Savonius rotor. Time, measured by a crystal (digital) clock that contained a low power oscillator as a timing source, was recorded only at the beginning of each sample burst.

Prior to deployment the four clocks were simultaneously reset to zero using WWV as a standard time source, and at the end of the experiment the clock times were compared to WWV time. The maximum long term

Table 3. Current meter and wind recorder malfunctions measured during pre-deployment testing.

Current meter	Malfunctions and Repairs
0285	Ground wire connection broke during routine handling.
0286	No apparent problems.
0287	Fifth significant bit in rotor-count electronics not active. Replaced CTR-1 board. Reed on/off switch intermittent. Requires vibration to open after removal of magnet.
0288	Discontinuity through plug J3-L. Plug contacts were bent slightly to insure good continuity.
Wind recorder	Fifth bit in CTR-1 board (E5) not active. Replaced board.

drift or error between WWV elapsed time and digital clock elapsed time was -90 seconds, i.e., all the current meters recorded each sample burst at the same time. The rated stability of the clock is ± 1.2 seconds/day and the maximum value of the measured stability was -1.8 seconds/day.

Each current meter was new and was checked and inspected according to the procedures outlined by the manufacturer and by McCullough and Tupper (1969). The malfunctions detected during this trial period are given in Table 3. The wind recorder is included in this table since it was a modified current meter.

When taken out of the water on 5 September the current meters were in good condition and there was virtually no evidence of marine fouling. All units were dry inside and all were operating, except unit 0286 which developed a short circuit during its month at sea. There were no signs of leakage of the vane and compass followers. However, the vane followers of each of the instruments contained an air bubble about 1 cm in length when the instrument was in a horizontal position. The compass follower of unit 0288 contained an air bubble approximately 2 cm in length.

4.2 Wind Recorder

The wind recorder (Figure 6), which was a modified Geodyne A-850 tape recording current meter operating in an upside-down position, recorded wind speed and direction with the same data format and with the same sampling rate as the four current meters. The mechanical clock was replaced by a digital clock counter that defined zero time as the time

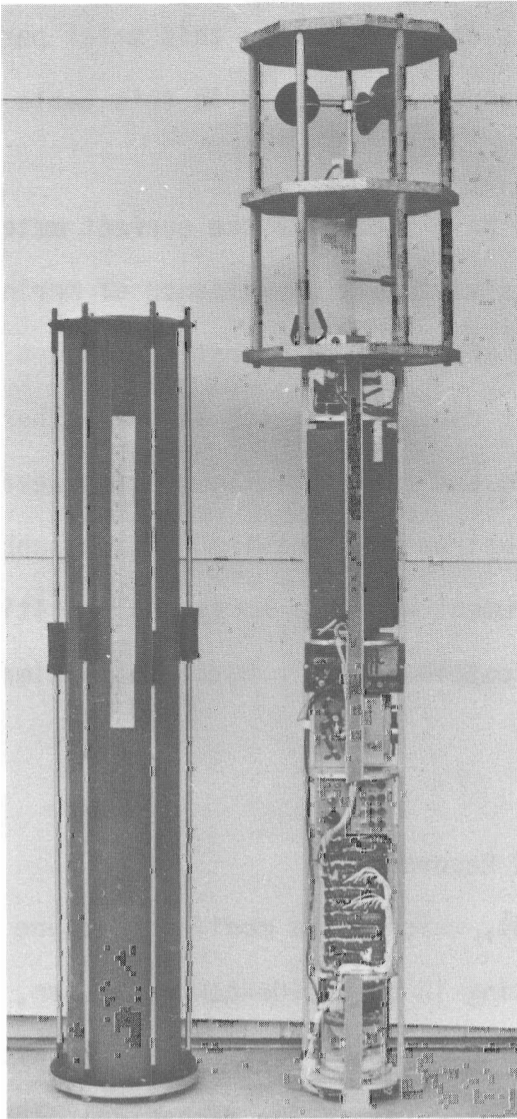


Figure 6: View of the wind recorder. The scale is given by the 30-inch ruler attached to the instrument case.

of the removal of the external magnet and, therefore, as the start time of the data recording. The aluminum housing was replaced with a lighter case made from polyvinylchloride (PVC). The external rotor and vane assembly of the current meter was replaced with another cage assembly containing a Geodyne model 141 3-cup anemometer and balanced wind vane.

The wind recorder was tested at wind speeds between 9 m/sec and 45 m/sec in the University of Washington Aeronautical Laboratory wind tunnel. At these speeds the angular displacement of the vane, which was probably due to vortex shedding caused by the standoffs, was small, i.e., about ± 5 degrees. Very small amplitude vertical oscillations of the cups were observed; however, no apparent errors were detected. At wind speeds greater than 25 m/sec the tie-rods vibrated with a very high frequency (strumming) and at 39 m/sec a nut threaded onto one of the tie-rods flew off. For the ocean experiment rubber bumper guards were placed on each of the tie-rods and the nuts were glued as well as threaded.

After the ocean experiment our anemometer was calibrated in the Department of Atmospheric Sciences, University of Washington wind tunnel which has a 4x4 square foot cross test section. A Beckman and Witey 3-cup anemometer, calibrated by the National Bureau of Standards, was used to measure tunnel wind speed. The anemometer cage was mounted on a specially designed fixture and the cups were approximately 35 cm above the tunnel floor. (The wind tunnel boundary layer thickness was about 4 cm.) Switch closures of our unit occurred once per revolution and were electronically counted for an interval of 1 minute.

For speeds between about 2 m/sec and 16 m/sec the average measured scale factor was approximately 39 counts per minute per m/sec (Figure 7). This value, which ignores the wind direction error due to the standoffs, is equal to the value obtained in a test conducted by Marchand (1968) for Geodyne Division, EG&G International.

The cups were subjected to tunnel speeds of 4.7, 7.8 and 11.6 m/sec; at each speed the unit was rotated in 10 degree increments for a total of 60 degrees, which is equal to the angular separation between the standoffs. The data in Figure 8 clearly indicate that the instantaneous scale factor and, therefore, the wind speed can vary as much as 12% from the average value (see also Marchand (1968)). However, a nominal scale factor of 39 rpm/m/sec, which ignores the nonlinearity associated with wind direction is probably well suited for computing the average wind speed recorded over some interval of time because natural winds are variable in direction, viz., over the recording interval, the high and low values of the instantaneous scale factors will balance. A more serious source of error is the inherent cup anemometer inaccuracies in gusty winds (Middleton and Spilhaus, 1953), i.e., in a variable wind the cup anemometer will register too high a mean wind speed because the cups accelerate more rapidly than they decelerate.

4.3 Temperature Profiler

The temperature profiler consisted of a digital temperature recorder (DTR) connected to a neoprene jacketed, strength membered multiconductor cable. The DTR was mounted in a stainless steel cage that

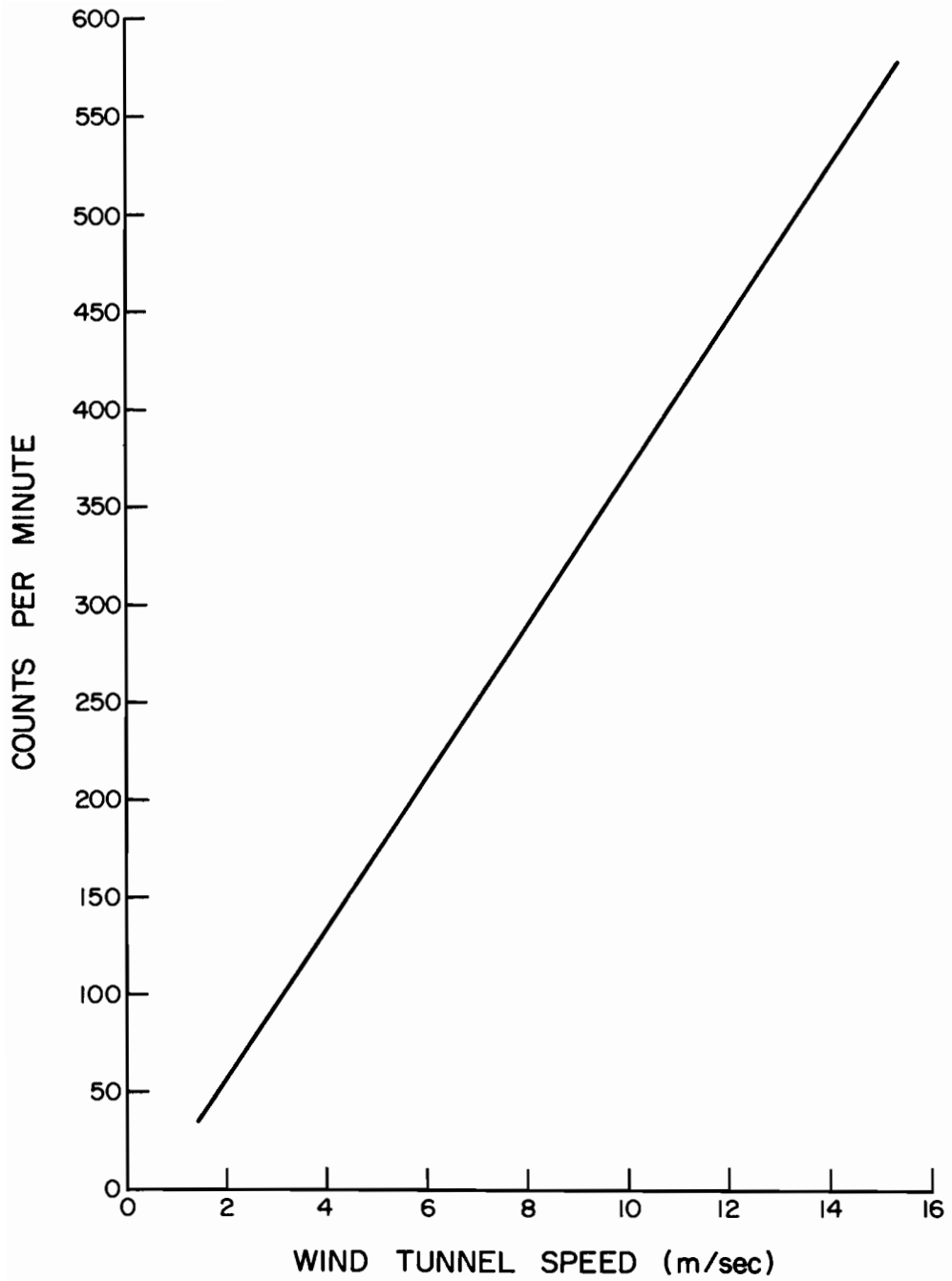


Figure 7. Anemometer calibration curve.

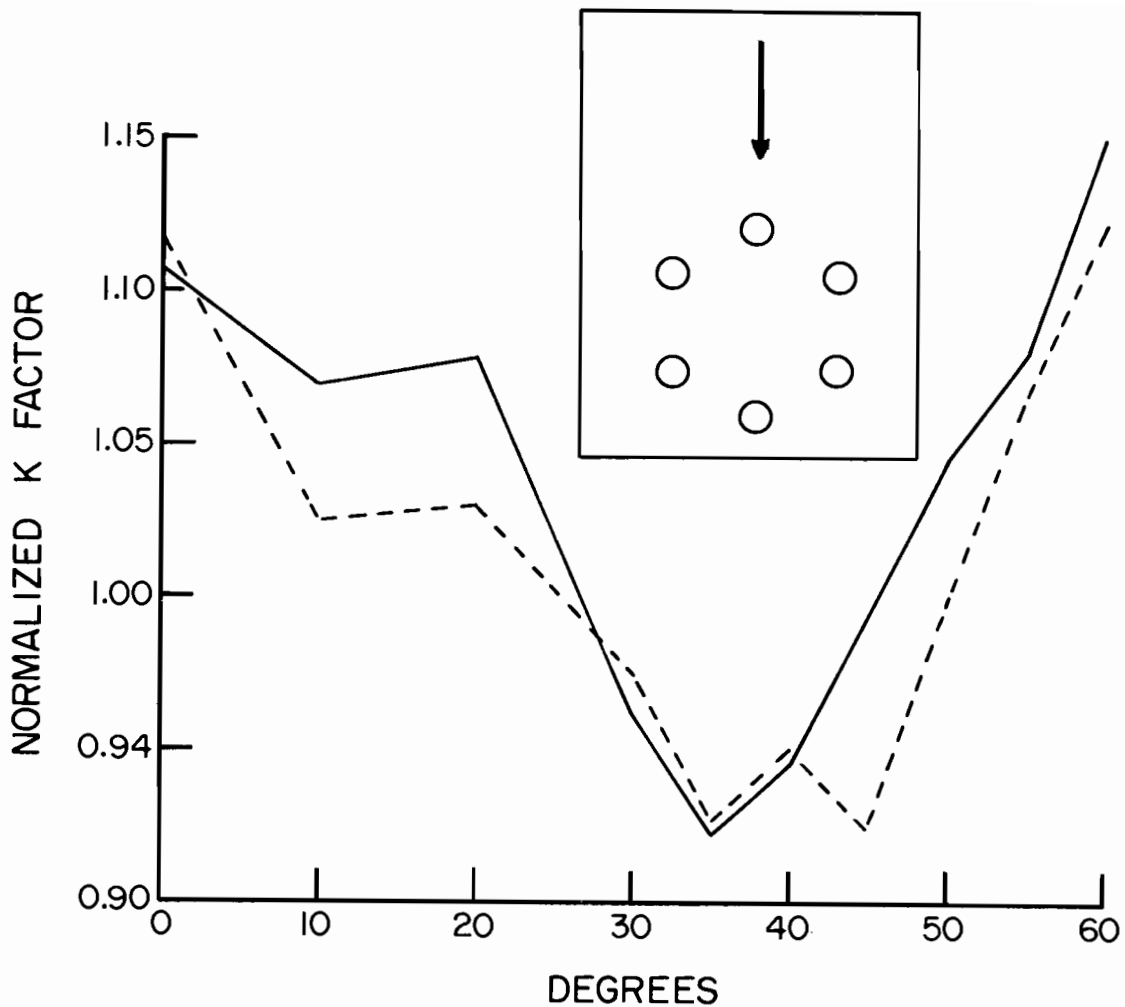


Figure 8. The slope of the anemometer calibration curve (K factor) at different azimuths between the wind direction and the standoffs. A K of 1.0 equals 39 counts per m/sec. The dashed and solid lines represent the K factors determined from wind speeds of 7.8 and 11.6 m/sec and of 4.7 and 7.8 m/sec, respectively.

was suspended in-line with the mooring cable. The termination of the neoprene cable was loosely connected to the upper end of the DTR (Figure 9). The uppermost thermistor was attached to the cage, while the other seven probes were mated to the conductor cable. Using Panduit nylon locking cable ties and Scotch 88 electrical tape the thermistor cable was tied to the mooring cable at one to two meter intervals with a small catenary occurring between tie points. It was secured to the current meter without any catenary and was fastened to the outside of one of the standoffs surrounding the rotor and vane (Figure 9).

4.3.1 Digital temperature recorder

The digital temperature recorder (DTR) was a version of the Geodyne Model A-775 tape recording temperature digitizer (Perry and Smith, 1965) that was modified extensively by the Pacific Oceanographic Laboratory. Originally, the instrument was designed to record temperature measurements made beneath the sediment-water interface for short time intervals. We increased the number of external inputs from six to nine by removing tilt switches that were used to measure the vertical angle of the heat probe. The resistance bridge was changed so that the warmer temperatures occurring in the upper regions of the ocean could be recorded. The mechanical clock was replaced with a digital clock counter, whose long term stability was an order of magnitude lower than the stability of the mechanical clock. The battery life of the instrument was doubled; i.e., for a 5 minute sampling interval the power supply was sufficient for about 40 days of operation.

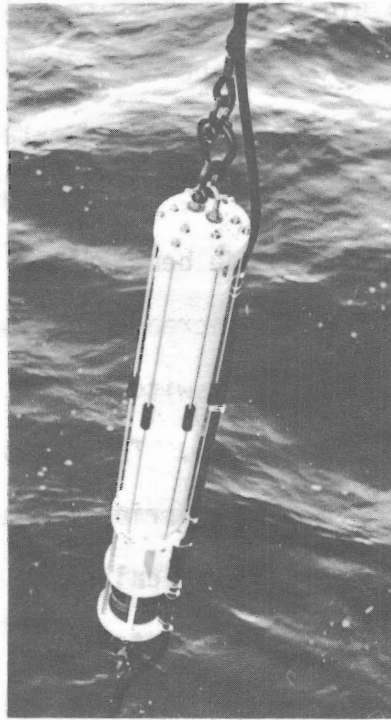
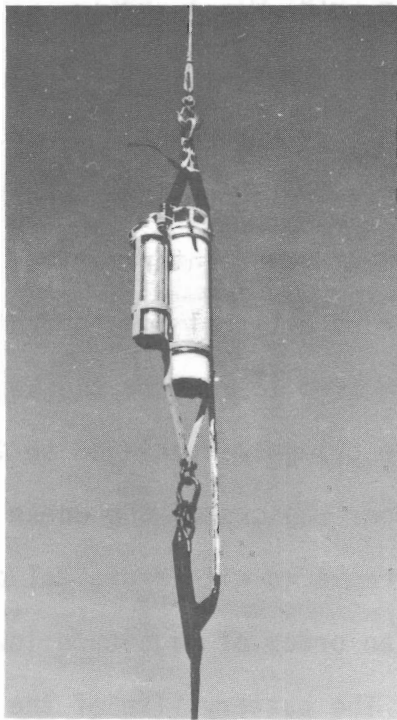


Figure 9. Left: View of the temperature profiler in-line with the mooring cable. Right: View of the thermistor cable and a current meter during deployment.

The central unit of the Geodyne instrument is a Wheatstone bridge and a high gain null-sensing amplifier. Two of the bridge arms contain fixed precision resistors, one arm consists of the thermistor and one arm contains a parallel ladder network of 12 precision resistors. The unit measures the resistance of a number of sensors by sequentially placing them in and out of the bridge. After a sensor is put into the bridge, the resistors in the ladder network are switched into the bridge arm beginning with the highest value. These resistors are left in or taken out as determined by the amplifier whose output indicates whether the bridge is underbalanced or overbalanced. This sequential balancing generates a 12 bit binary word proportional to the conductance of the ladder network. The resolution of the 12 bit binary number is 2.5 ohms. Approximately 5 seconds are required to sample the 12 input channels of the DTR, which were a sample count generated by the clock, eight thermistors and a reference resistor that were mated to a neoprene multiconductor cable, a reference resistor inside the instrument case and one blank channel. The DTR recorded this data block at 5 minute intervals on the same type of magnetic tape cartridges used in the current meters.

We determined that the internal noise of the DTR was negligible because the same binary number was recorded by each channel when a single high precision resistor was connected to all inputs.

4.3.2 Thermistors

The temperature sensor was a Yellow Springs Model 403 thermistor encapsulated in a stainless steel tube. Twenty units were calibrated in a constant temperature bath at the Applied Physics Laboratory, University of Washington. The time constant of the thermistor was about 3.4 seconds and the temperature bath maintained $\pm 0.001^\circ\text{C}$ during each of the calibration measurements, which were made with a quartz crystal thermometer and a decade resistance box that had resolutions of $\pm 0.001^\circ\text{C}$ and 0.1 ohms, respectively. Eight sets of measurements were least squares fitted to the Steinhart and Hart (1968) resistance-temperature function for thermistors, which is

$$\frac{1}{T} = A + B (\ln R) + C (\ln R)^3 \quad (1)$$

where T is the temperature in degrees Kelvin, R the resistance in kilohms and A, B and C are empirical constants. The results of fitting the calibration data to the equation are shown in Table 4. Clearly the fit is good as the maximum temperature residuals are approximately the same size as the experimental error. Since the resolution of a resistance measurement recorded by the DTR was 2.5 ohms, the ultimate resolution of the temperature profiles for the range 4°C to 16°C varied between 0.018°C and 0.008°C (Figure 10).

The time constant of each thermistor (i.e., the time required for the thermistor to change 63% of the difference between its initial and final temperatures) was increased to about 6.5 minutes by inserting the stainless steel probe into a nylon slug (Figure 11).

Table 4. Numerical coefficients of the thermistors and the results of fitting the calibration data to equation (1), i.e., the maximum temperature residuals between the measured and calculated values, and the temperature at which it occurred, are shown.

Thermistor	Empirical Constants			Maximum Residuals	
	$A \times 10^3$	$B \times 10^4$	$C \times 10^7$	Temp, °C	Residual, °C
1	3.145393	2.562376	6.025695	13.949	- .0020
2	3.145907	2.564409	6.053511	13.949	- .0018
3	3.146352	2.560785	5.675238	8.020	- .0015
4	3.144757	2.567359	5.052612	8.020	- .0036
5	3.145318	2.563576	5.116060	11.981	.0018
6	3.145630	2.557872	5.518093	13.949	- .0017
7	3.144546	2.565703	5.736623	13.949	- .0016
8	3.145313	2.563130	5.614426	8.020	- .0017
9	3.145399	2.565497	5.091871	8.020	- .0048
10	3.145925	2.560729	5.843694	6.508	- .0041
11	3.144500	2.562119	5.751516	8.020	.0037
12	3.145338	2.563177	5.649613	11.981	.0009
13	3.145664	2.564030	5.828339	13.949	- .0012
14	3.144945	2.562879	5.414755	9.523	.0014
15	3.145410	2.563690	5.917312	11.981	.0016
16	3.145862	2.564913	5.435419	8.020	.0022
17	3.144684	2.566492	5.809398	13.949	.0010
18	3.144947	2.564403	5.403450	13.949	.0014
19	3.145103	2.562238	5.229496	13.949	.0015
20	3.145846	2.562724	5.907619	8.020	- .0012

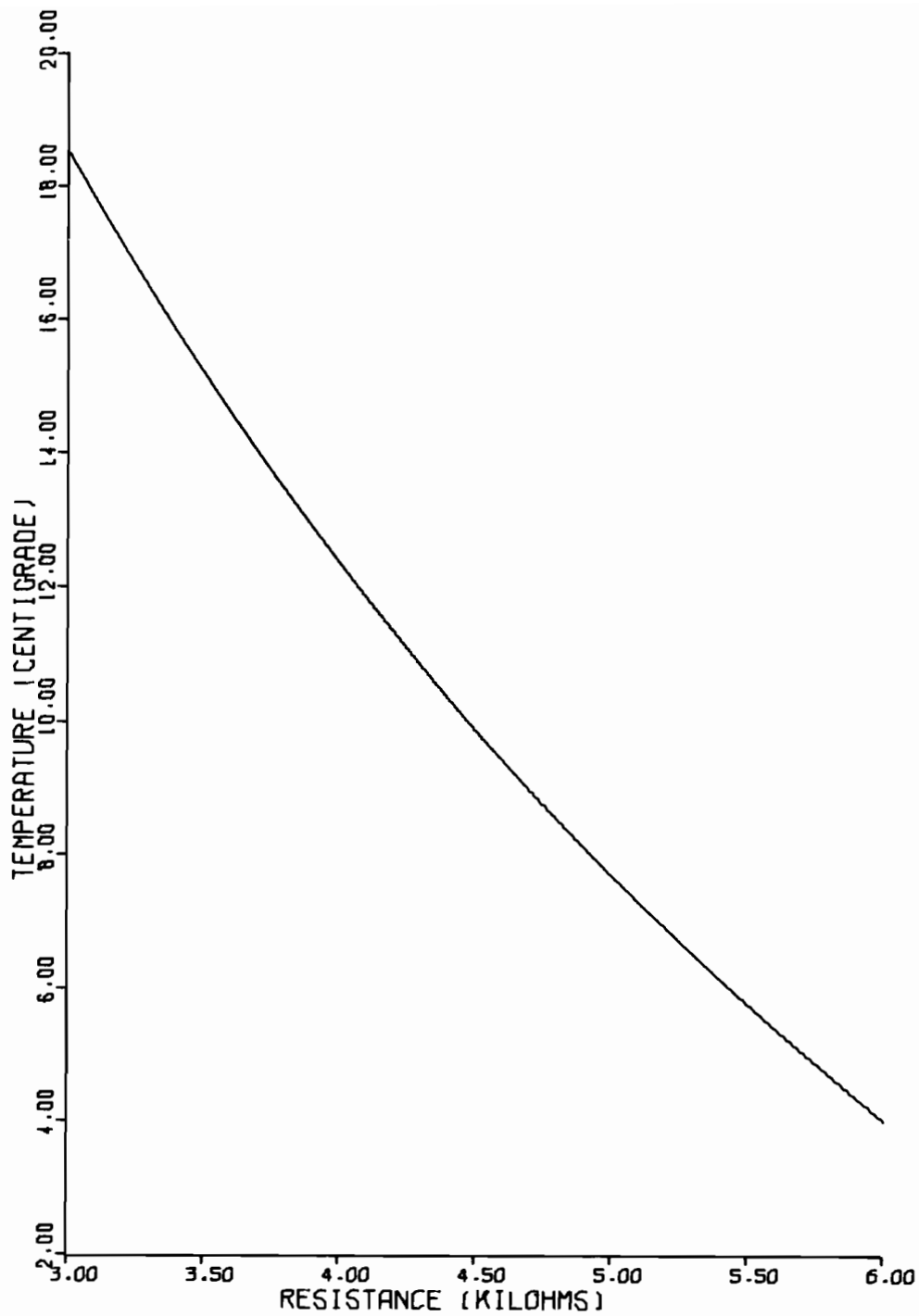


Figure 10. Thermistor (number 12) calibration curve computed from equation (1) and the coefficients given in Table 4.

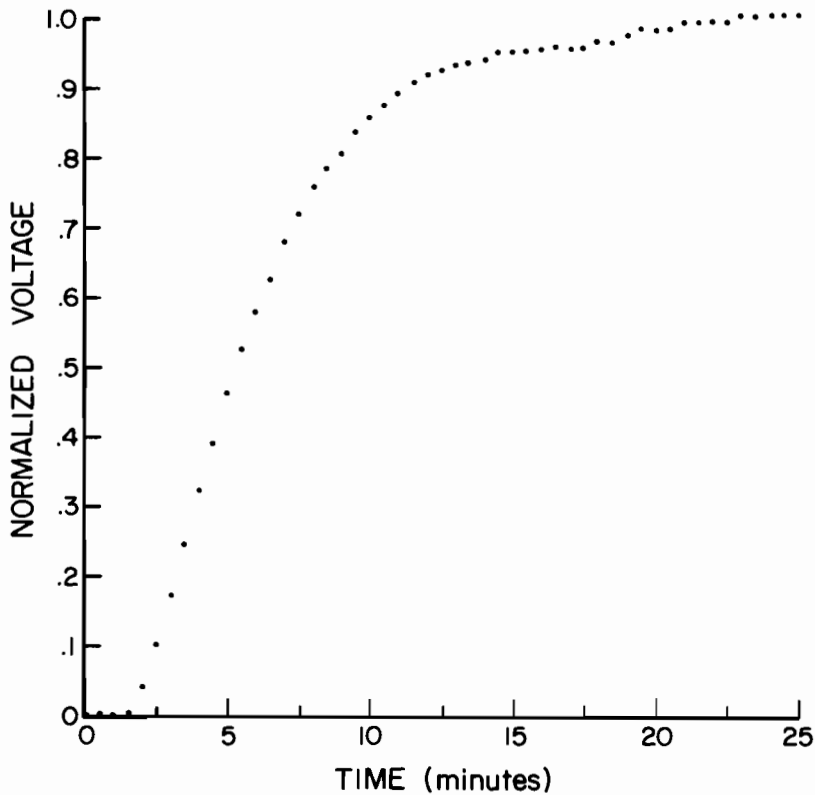
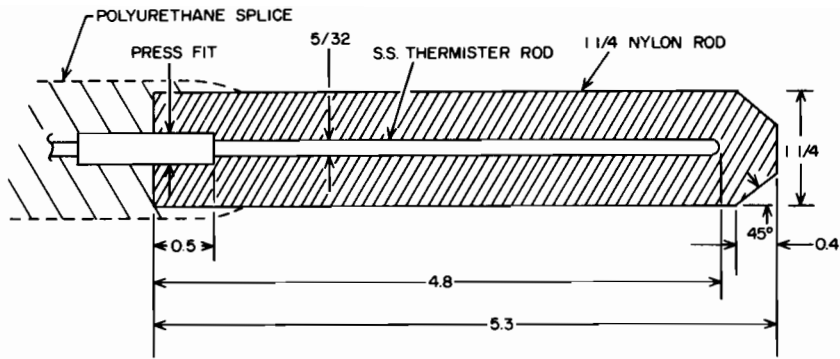


Figure 11. Upper: Cross sectional view of thermistor assembly. Dimensions are in inches. Lower: Time response of thermistor assembly to a step increase in temperature. The potential drop across the thermistor assembly was amplified and recorded on a digital voltmeter.

The maximum rise in temperature caused by the self heating of the thermistor was estimated to be about 0.001°C , which was below the measurement resolution of the instrument. The negligible amount of self heating resulted from the short sample time (0.4 seconds), the low bridge voltage (0.6 volts) and the relatively small resistance of the thermistor (about 3500 ohms at 16°C).

To determine the resolution between the thermistors, which was defined as the absolute value of the temperature range occurring between the probes, the temperature profiler was operated with a 5 minute sampling interval in a small windowless room for about 15 hours on the night of 28-29 July. The thermistor cable was made into a 1-meter diameter coil and suspended from the ceiling so that all the thermistors were at about the same height. The average resolution between the eight thermistors was about 0.08°C . However, smaller temperature differences occurred between probes that would be adjacent to one another when the cable was attached to the mooring system.

4.3.3 Thermistor cable

The South Bay neoprene jacketed multiconductor cable was fully blocked to prevent hosing and contained a 6.4 mm diameter wire rope strength member (rated breaking strength equal to 2270 kg) with eyes at both ends. The conductors consisted of twenty #18 gauge wires that terminated in pairs at 10 break-outs at 6.1 meter intervals.

The maximum calculated line resistance (associated with the thermistor located at 55 meters below the surface) was less than the

2.5 ohm resolution of the DTR. (The rated resistance of #18 gauge wire is 13.4 ohms/km.)

For three days beginning on 12 July the temperature profiling system was left on the bottom of Lake Union, Seattle. Temperature was sampled at 15 second intervals and both channels of the magnetic tape were completely filled with data. There were no signs of leakage.

4.4 Pressure and Temperature Recorder

The pressure and temperature recorder was a Braincon type 531 thermograph and depth recorder that measures temperature on 70-mm film as it passes between a phosphorescent light source and a mercury column in a glass thermometer. The temperature range was -2°C to 20°C , the accuracy was defined as $\pm 0.2^{\circ}\text{C}$ and the thermal response for 95% of full value was given as 10 minutes. The pressure sensor, which was a helical Bourdon tube connected to an arm having a luminous point, had a range of 0 to 200 pounds/sq. inch (or 0 to 140 meter depth) and an accuracy rated as ± 2 psi (or ± 1.4 meters). A measurement of temperature and pressure was recorded every 10 minutes. The stability of the timing mechanism was defined as ± 2 seconds/day.

The accuracy and sensitivity of the pressure element were tested from the Evergreen Floating Bridge which crosses Lake Washington, Seattle. The instrument was suspended at the end of a measured line and lowered to selected depths for different intervals of time. A comparison between depths measured by the instrument and depths determined from the amount of line in the water shows clearly (Table 5) that the

Table 5. Results of an experimental examination of the sensitivity and accuracy of the pressure (depth) sensing element of the Braincon thermograph and depth recorder. Pressure to depth conversion defined by: depth (meters) = 0.7030696* pressure (pounds/inch²). The sampling interval of the instrument was 10 minutes.

Length of line method Depth (meters)	Data analysis method		
	Number	Depth* (meters)	Stand dev (meters)
50	153	50.2	.16
40	130	41.2	.08
38	159	38.9	.32
36	325	36.3	.31
34	73	34.1	.16
32	317	31.3	.24
28	460	27.5	.28

*Corrected for sea surface reading of -2.1 meters

accuracy of the depth measuring element was equal to the accuracy defined by the manufacturer. It is of interest to note that the measurements obtained at each depth appear to be normally distributed about the mean, i.e., for the 7 data sets the average skewness was -0.04 and the average kurtosis was 3.31.

4.5 Atmospheric Pressure Recorder

The atmospheric pressure recorder consisted of a Rustrak Model 288 strip chart recorder and a Sostman Model 2014 aneroid barometer that converts barometric pressure into electrical resistance. The resistance output was changed to a voltage which then passed through a first order low-pass filter with a time constant of 5 minutes (Figure 12). The range of the pressure sensor was 950 to 1050 mb or 0 to 3000 ohms, and according to the 10-point calibration supplied by the manufacturer, the pressure-resistance function was linear to within 3 mb. Figure 13 shows the instrument calibration determined with a decade resistance box in place of the pressure cell. The resolution of the pressure sensor was given as approximately 1 mb.

The chart paper advance rate was 0.5 inches/hour with a $\pm 1\%$ accuracy and the writing speed was 1 strike per 2 seconds. For better time control we used an Accutron timer with a rated stability of ± 2 seconds/day to drive a relay that put hourly tic marks on the chart paper. The measured drift of our timing mechanism was -2.6 seconds/day. This clock assembly also put hourly tic marks on the chart papers contained in the air-sea surface temperature recorders.

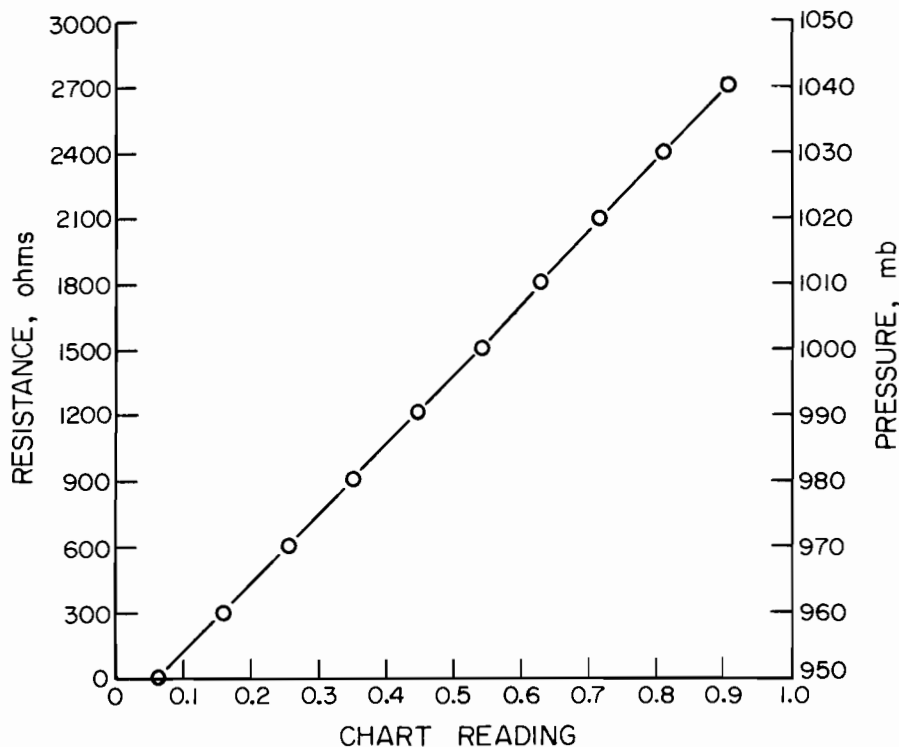
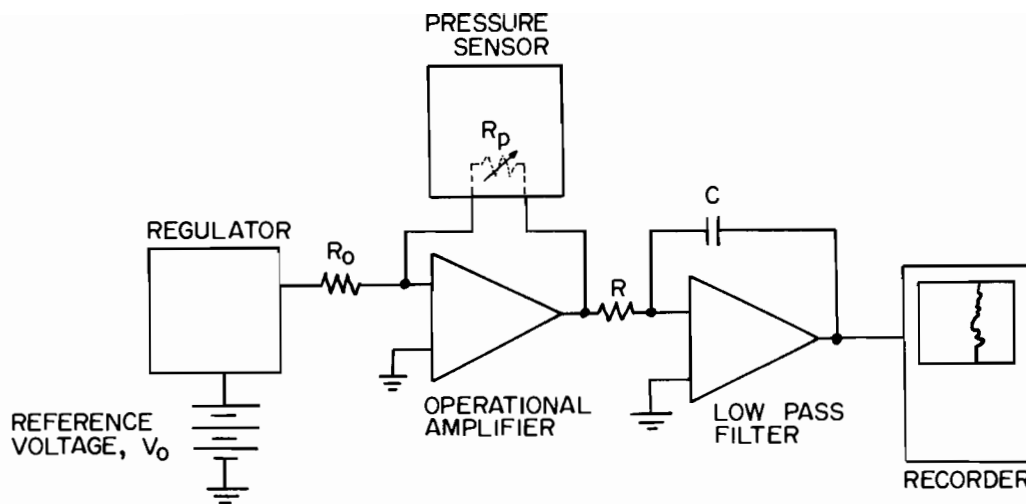


Figure 12. Upper: Schematic diagram of the atmospheric pressure recorder. An operational amplifier multiplied a reference voltage V_0 by R_p/R_0 , a factor between 0 and 1, and the signal $V_0 (R_p/R_0)$ was passed through a filter before recording it. The power supply consisted of a 12 volt, 24 amp-hour lead-acid battery and two 7.5 volt, 2 amp-hour dry cells. Lower: Calibration curve of the atmospheric pressure recorder. Chart width equals 2 inches.

The elements of the atmospheric pressure recorder were housed in a plywood box which contained a 4 cm square plexiglass window over the chart paper. The pressure transducer was in contact with the atmosphere through a 2.5 mm diameter hole in the side of the box.

After 17 days the take-up spool of the Rustrak recorder jammed.

4.6 Air and Sea Surface Temperature Recorder

The air and sea surface temperature recorder, which consisted of a dual channel Rustrak Model 2133B thermistor probe recorder and two Yellow Springs thermistors inserted into nylon slugs measured the temperature of the atmosphere near the sea surface and the temperature of the water near the atmosphere with an accuracy of about $\pm 0.4^{\circ}\text{C}$ and a resolution of about $\pm 0.1^{\circ}\text{C}$. The time constant of the temperature probe assembly was approximately 6.5 minutes (see Figure 11). The chart speed was 0.5 inches/hour and the writing speed of each channel was 1 strike every 2 seconds. Hourly tic marks controlled by the Accutron timer contained in the atmospheric pressure recorder were put on the chart paper. The strip chart recorder and a 12 volt, 24 amp-hour lead-acid battery were housed in a plywood box.

The water-measuring thermistor assembly was attached to a horizontal stainless steel tube welded to the bottom of the toroid (Figure 2) and the air-measuring thermistor assembly was enclosed in a radiation shield that permitted a free flow of air (Figure 13).

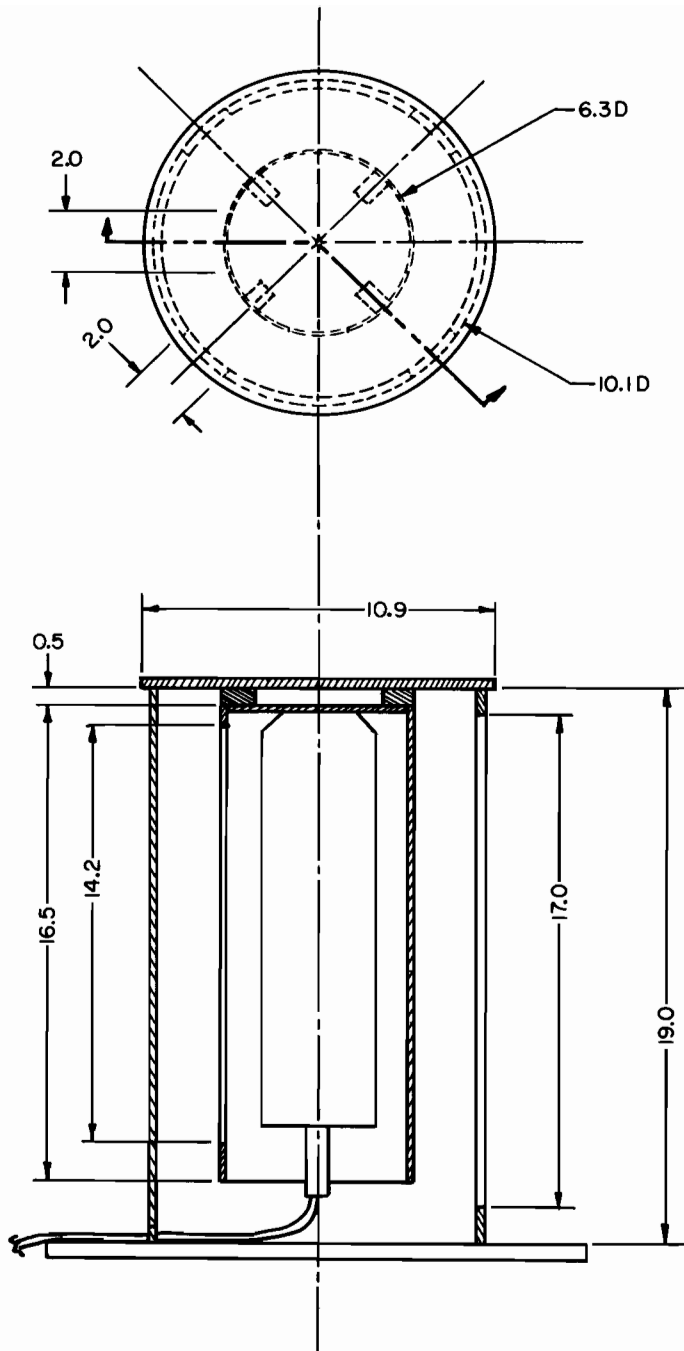


Figure 13. View of the radiation shield of the air measuring thermistor assembly.

Two instruments were assembled. After 10 days excessive moisture destroyed one unit and the take-up spool of the Rustrak recorder of the other unit jammed after 17 days.

4.7 Tension Meter

The Swift Model 5-701 tension meter, which records the pull of the mooring cable attached to the bottom of the instrument, utilizes a piston to compress a given volume of oil connected to a Bourdon pressure gauge and the resulting oil pressure deflects the needle of a Rustrak recorder. The ambient pressure is applied on both sides of the piston to compensate for depth effects. The range of our unit was 0 to 5000 pounds and the accuracy was given as ± 100 pounds. The chart paper speed was 0.5 inches per hour, the data was recorded at 2 second intervals, and the tension record was a cluster of dots of varying density. For better time control a clock put hourly tic marks on the chart paper.

4.8 Acoustic Release

The American Machine and Foundry Model 242 acoustic release system, which has been reviewed by Heinmiller (1968) and by the National Oceanographic Instrumentation Center (1971b), consisted of an underwater acoustic release and pinger and a shipboard command unit. Before deployment of the mooring the submerged unit was lowered to 1000 meters depth and fired.

4.9 Navigation Aids

The location and tracking equipment of the deep sea mooring consisted of an Alpine Model 430MA X-band radar transponder, a Geodyne Model A-358 radar reflector, a Geodyne Model A-180 flashing xenon buoy light and the surface float with its day-glo orange color. The buoy light was visible at distances of about 3 miles. A maximum transponder range of 6 miles was determined with the ship's radar. According to the manufacturer this low range was due to defective parts in the receiver section. The unit was not operating when we arrived at the buoy site on 5 September because water had collected in the power plug connecting the transponder to a 12 volt, 100 amp-hour lead-acid battery contained in a plywood box.

5. ACKNOWLEDGEMENTS

The experimental investigation described in this report benefited from the assistance provided by numerous organizations and individuals.

I am indebted to M. Reynolds, Pacific Oceanographic Laboratory (POL), who constructed the wind recorder, the temperature profiler, the atmospheric pressure recorder and the air and sea surface temperature recorder, and who calibrated and tested all the instruments. Assistance provided by J. Stephens (POL) is gratefully acknowledged.

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The officers and crew of the NOAA Ship OCEANOGRAPHER (Captain M. Tonkel commanding) are highly commended for their excellent support. I am grateful to Cmdr. J. Randall for his aid during the deployment and recovery of the mooring.

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6. APPENDIX A

Mooring Components Used Between the Toroidal Buoy and the Anchor

Toroidal buoy with three 1-inch diameter eyes

Three 3/4 inch safety anchor shackles with welded bolt-nuts
safe working load = 9500 lbs.
weight = 2.82 lbs.
length = 3.52 inches

Three 5/8 inch safety anchor shackles with welded bolt-nuts
safe working load = 6500 lbs.
weight = 1.58 lbs.
length = 3 inches

Three pieces of 9.84 feet of 5/8 inch high test chain wrapped with fire hose
working load = 11,500 lbs.
weight = 4.5 lbs. per foot

Three 5/8 inch safety anchor shackles with welded bolt-nuts

1 inch weldless sling link (or pear shaped link)
weight = 4.3 lbs.
length = 8 inches

5/8 inch safety anchor shackle with welded bolt-nut

3 feet 3 inches of 5/8 inch high test chain wrapped with fire hose

5/8 inch safety anchor shackle with welded bolt-nut

Model D, type 2 Miller swivel with welded bolt-nuts
weight = 9.5 lbs.
length = 10.19 inches

3/8 inch extra heavy wire rope thimble
weight = 0.25 lbs.

ESCO duplex sleeve swaged fitting

3 feet 3 inches of 3/8 inch 3x19 Amgal wire rope
weight = 0.22 lbs/foot
breaking strength = 14,800 lbs.

ESCO duplex sleeve swaged fitting

3/8 inch extra heavy wire rope thimble

5/8 inch anchor shackle
weight = 1.44 lbs.
length = 3 inches

3/4 inch weldless sling link
safe working load = 6000 lbs.
weight = 1.9 lbs.
length = 6 inches

5/8 inch anchor shackle

3/4 inch weldless sling link

5/8 inch anchor shackle

Current meter 0285
weight in water = 40 lbs.
length = 6 feet

5/8 inch anchor shackle

3/8 inch extra heavy wire rope thimble

ESCO duplex sleeve swaged fitting

3 feet 3 inches of 3/8 inch 3x19 Amgal wire rope

ESCO duplex sleeve swaged fitting

3/8 inch extra heavy wire rope thimble

5/8 inch anchor shackle

3/4 inch weldless sling link

5/8 inch anchor shackle

Digital temperature recorder cage with digital temperature recorder
weight = 65 lbs.
length = 60 inches

5/8 inch anchor shackle

3/4 inch weldless sling link

The multiconductor strength-membered neoprene cable containing the thermistors was attached to the 3/4 inch weldless sling link directly beneath the digital temperature recorder cage with a 3/8 inch anchor shackle. This cable was mated to the wire rope and to the current meters with tape and nylon bands at 1 to 2 meter intervals. The

weight of this cable was about 110 lbs.

5/8 inch anchor shackle

3/8 inch extra heavy wire rope thimble

ESCO duplex sleeve swaged fitting

7 feet 3 inches of 3/8 inch 3x19 Amgal wire rope

ESCO duplex sleeve swaged fitting

3/8 inch extra heavy wire rope thimble

5/8 inch anchor shackle

3/4 inch weldless sling link

5/8 inch anchor shackle

Current meter 0286

5/8 inch anchor shackle

3/4 inch weldless sling link

5/8 inch anchor shackle

3/8 inch extra heavy wire rope thimble

ESCO duplex sleeve swaged fitting

26.2 feet of 3/8 inch 3x19 Amgal wire rope

ESCO duplex sleeve swaged fitting

3/8 inch extra heavy wire rope thimble

5/8 inch anchor shackle

3/4 inch weldless sling link

5/8 inch anchor shackle

Current meter 0287

5/8 inch anchor shackle

3/4 inch weldless sling link

5/8 inch anchor shackle
3/8 inch extra heavy wire rope thimble
ESCO duplex sleeve swaged fitting
57 feet 7 inches of 3/8 inch 3x19 Amgal wire rope
ESCO duplex sleeve swaged fitting
3/8 inch extra heavy wire rope thimble
5/8 inch anchor shackle
3/4 inch weldless sling link
5/8 inch anchor shackle
Current meter 0288
5/8 inch anchor shackle
3/4 inch weldless sling link
5/8 inch anchor shackle
3/8 inch extra heavy wire rope thimble
ESCO duplex sleeve swaged fitting
142 feet of 3/8 inch 3x19 Amgal wire rope
ESCO duplex sleeve swaged fitting
3/8 inch extra heavy wire rope thimble
5/8 inch anchor shackle
3/4 inch weldless sling link
1/2 inch anchor shackle
 safe working load = 4000 lbs.
 weight = .74 lbs.
 length = 2.38 inches
Pressure/temperature recorder
 weight in water = 20 lbs.
 length = 3 feet
1/2 inch anchor shackle

3/4 inch weldless sling link
5/8 inch anchor shackle
3/8 inch extra heavy wire rope thimble
ESCO duplex sleeve swaged fitting
981 feet 3 inches of 3/8 inch 3x19 Amgal wire rope
ESCO duplex sleeve swaged fitting
3/8 inch extra heavy wire rope thimble
5/8 inch anchor shackle
3/4 inch weldless sling link
5/8 inch anchor shackle
3/4 inch weldless sling link
Model D, type 2 Miller swivel with welded bolt-nuts
3/4 inch weldless sling link
5/8 inch anchor shackle
Tension meter
 weight in water = 25 lbs.
 length = 3 feet
1/2 inch safety anchor shackle with welded bolt-nuts
 safe working load = 4000 lbs.
 weight = .82 lbs.
 length = 2.38 inches
3/4 inch weldless sling link
5/8 inch anchor shackle
3/4 inch thimble with preventer ears made with nylon bands
Eye splice, 4 tucks
1640 feet (500 meters) of 3/4 inch plaited Pli-Moor nylon line
Eye splice, 4 tucks
3/4 inch thimble with preventer ears made with nylon band

5/8 inch anchor shackle
3/4 inch weldless sling link
5/8 inch anchor shackle
3/4 inch thimble with preventer ears made with nylon bands
Eye splice, 4 tucks
1640 feet (500 meters) of 3/4 inch plaited Pli-Moor nylon line
Eye splice, 4 tucks
3/4 inch thimble with preventer ears made with nylon bands
5/8 inch anchor shackle
3/4 inch weldless sling link
5/8 inch anchor shackle
3/4 inch thimble with preventer ears made with nylon bands
Eye splice, 4 tucks
1640 feet (500 meters) of 3/4 inch plaited Pli-Moor nylon line
Eye splice, 4 tucks
3/4 inch thimble with preventer ears made with nylon bands
5/8 inch anchor shackle
3/4 inch weldless sling link
5/8 inch anchor shackle
3/4 inch thimble with preventer ears made with nylon bands
Eye splice, 4 tucks
984 feet (300 meters) of 3/4 inch plaited Pli-Moor nylon line
Eye splice, 4 tucks
3/4 inch thimble with preventer ears made with nylon bands
5/8 inch anchor shackle

3/4 inch weldless sling link

5/8 inch anchor shackle

Model D, type 2 Miller swivel with welded bolt-nuts

3/4 inch weldless sling link

5/8 inch anchor shackle

Acoustic release

weight in water = 70 lbs.

length = 51 inches

5/8 inch anchor shackle

3/8 inch extra heavy wire rope thimble

ESCO duplex sleeve swaged fitting

750 feet of 3/8 inch 3x19 Amgal wire rope

ESCO duplex sleeve swaged fitting

3/8 inch extra heavy wire rope thimble

5/8 inch anchor shackle

3/4 inch weldless sling link

5/8 inch safety anchor shackle with welded bolt-nut

32.8 feet of 5/8 inch high test chain

5/8 inch safety anchor shackle with welded bolt-nut

1 inch weldless sling link

5/8 inch safety anchor shackle with welded bolt-nut

Three pieces of 9.84 feet of 5/8 inch high test chain

Three 5/8 inch safety anchor shackles with welded bolt-nuts

Anchor with 3 eye-bolts

weight = 4000 lbs.

7. APPENDIX B

Cruise Milestones

- Julian Day 193 (July 12) Load nylon line, wire rope, uninstrumented surface float and anchor aboard NOAA Ship OCEANOGRAPHER in Seattle.
- Julian Day 213 (August 1) Depart Seattle by truck. Arrive Port Angeles. Load oceanographic and meteorological instruments and mooring equipment aboard OCEANOGRAPHER. Uncase digital temperature recorder, current meters and wind recorder for final checkout and inspection. Mount equipment on surface float.
- Julian Day 214 Mount equipment on surface float. Depart Port Angeles. Test fire acoustic release at 1000 meters depth.
- Julian Day 215 Rearm acoustic release. STD cast 1001. Bathymetric survey. Deploy surface float and mooring.
- Julian Day 216 Anchor dropped (0016 GMT). STD casts 1002-1005.
- Julian Day 217 STD casts 1006-1015. Bathymetric survey.
- Julian Day 218 STD casts 1016-1019. Bathymetric survey.
- Julian Day 248 (September 5) STD casts 1020-1022. Retrieval of buoy and equipment. Acoustic release fired 1625 GMT. STD cast 1023. Uncasing of instruments.
- Julian Day 249 STD casts 1024-1034. Bathymetric survey. Uncasing of instruments.
- Julian Day 250 STD casts 1035-1038. Bathymetric survey.

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