CURRENT METER OBSERVATIONS OF THE CIRCULATION IN GRAND TRAVERSE BAY OF LAKE MICHIGAN: MOORING METHODS AND INITIAL RESULTS

By

Richard G. Johnson
and
Edward C. Monahan

Department of Meteorology and Oceanography
College of Engineering
The University of Michigan

November 1971

Sea Grant Technical Report #18

THE UNIVERSITY OF MICHIGAN SEA GRANT PROGRAM

TABLE OF CONTENTS

Section — Page No.

LIST OF FIGURES AND TABLES 4-5

ACKNOWLEDGMENTS 6

INTRODUCTION 8

SUB-SURFACE BUOYS 12

- Sub-surface Float, First Design and Construction 12
- Sub-surface Float, Second Design and Construction 13

CURRENT METER MOORINGS 21

- Mooring A 21
  - Purpose 21
  - Description 21
  - Narrative 23
  - Remarks 28
- Mooring B 29
  - Purpose 29
  - Description 29
  - Narrative 31
  - Remarks 35
- Mooring C 36
  - Purpose 36
  - Description 36
  - Narrative 36
  - Remarks 36

Section	Page No.
Mooring D	37
Purpose	37
Description	37
Narrative	37
Remarks	37
Mooring E	39
Purpose	39
Description	39
Narrative	39
Remarks	39
DATA SUMMARY - PRELIMINARY RESULTS	42
Mooring A	43
Comments on Results	43
Mooring B	51
Comments on Results	51
REFERENCES	58

LIST OF FIGURES

Figure	Description	Page No.
1	Chart of Grand Traverse Bay	11
2	Polyurethane Buoy: Foaming Process	14
3	Polyurethane Buoy: Specifications	15
4	Polyurethane Buoy: Completed Assembly	16
5	Sub-surface Adjustable Buoyancy Assembly (SABA)	18
6	S.A.B.A.: Specifications	18
7	Drag Force Calculations on Sub-surface Buoy	20
8	Mooring A: Design	22
9	Research Vessel SEA GRANT I	24
10	Mooring A: Recovery	27
11	Polyurethane Buoy: Ice and Pressure Damage	27
12	Mooring B: Design	30
13	Mooring A: Anchor Setting	32
14	Meter Extraction from Sub-surface Instrument Array	34
15	Direction Histogram: Mooring A	44
16	Speed Histogram: Mooring A	46
17	Time Histogram: Mooring A	47
18	Progressive Vector Diagram: Mooring A	49
19	Direction Histogram: Mooring B	52
20	Speed Histogram: Mooring B	53
21	Time Histogram: Mooring B	54

Figure	Description	Page No.
22	North-East Velocity Component Diagram: Mooring B	56
23	Progressive Vector Diagram: Mooring B	57

LIST OF TABLES

Table	Description	Page No.
1	Buoyancy and Array Length Versus Angle of Deviation	20

ACKNOWLEDGMENTS

The research activities described in the following report benefited from the assistance provided us by numerous organizations and individuals.

At the outset of this project we gained insights into up-to-date current meter mooring techniques by participating in a two-week cruise aboard the Woods Hole Oceanographic Institution's R/V KNORR, with Mr. R. Heinmiller as Chief Scientist. The practical aid and suggestions provided us by Mr. H. Armstrong and Mr. G. Tupper of W.H.O.I. are acknowledged, as is the invaluable assistance given us by Miss Susan Tarbell, who introduced us to the W.H.O.I. current meter data analysis procedures. We thank Dr. F. Webster of the W.H.O.I. for making their data handling facilities available to us.

Assistance in the field was provided by Mr. E. Michelena, Mr. G. Goldman, Mr. W. Heath, Mr. T. Kaye, and Mr. L. Pocalujka, all participants in our Water Circulation Project. Mr. C. Craw operated the R/V SEA GRANT I during our numerous mooring and tending operations. Dr. L. Somers, Mr. P. Blackburn, and Mr. W. Michaels, of the University of Michigan's Underwater Operations Group, provided us with diving services on many occasions. Mr. R. Borys, Mr. D. Deitemyer, Mr. R. Seeger, and Mr. J. Sygo assisted in the construction of the buoys. Miss Irene Barinoff and Mr. T. Kaye helped prepare the mooring illustrations.

We wish to thank Prof. F. Michelsen for the use of the U-M Naval Architecture and Marine Engineering Tow Tank during the testing of our sub-surface buoys.

We are most grateful to Northwestern Michigan College in Traverse City, and to its president Dr. J. Davis, for putting at our disposal their facilities. We particularly want to acknowledge the assistance of Capt. W. Hemmick and Mr. J. Gamboe of N.M.C.'s Great Lakes Maritime Academy.

The aid we received from the U.S. Coast Guard Air Station in Traverse City during the recovery of Mooring A is gratefully acknowledged. We thank Cmdr. Jahnsen, Lt. Cmdr. Brothers, and Lt. Morgan for their helicopter spotting.

Dr. C. Clay, Mrs. J. Clay, and Mr. T.-K. Kan of the Geophysical and Polar Research Center, Department of Geology and Geophysics, The University of Wisconsin, came to our aid with their side-scanning sonar unit during our search for Mooring E. We are most grateful for their cooperation.

The assistance provided us by several firms in the Grand Traverse Bay area should not go unrecognized. The Rennie Oil Company allowed us to use their pier during the recovery of Mooring A and donated empty anchor drums. Concrete Service, Inc. of Traverse City donated the concrete to fill these drums which constituted our anchors. Mr. L. Spears of Northport Sport Trollers Charter Service assisted in the search for Mooring E.

INTRODUCTION

As part of an intensive study of Grand Traverse Bay of Lake Michigan under the Sea Grant Program of The University of Michigan, an investigation of the currents, periodic and aperiodic, has been undertaken. The current measurements obtained during this investigation, coupled with meteorological observations (Goldman, 1971) and determinations of the thermal structure of the bay, are expected to provide the basis for an identification of the several physical mechanisms which induce the circulation within this body of water. These observations will also be used in the verification of mathematical models of the wind-driven circulation of the bay, which are currently being formulated.

An understanding of the bay's response to the various meteorological factors, and the ability to predict these responses, are necessary inputs in any effort to model the distribution of nutrients, sediment, and pollutants, and will be valuable in ecological emergencies, such as would arise if there were a bulk oil spill from one of the tankers that visit this bay.

A previous attempt to interpret the circulation in Grand Traverse Bay (Lauff, 1957) was judged not to be of significant use in the present study because of the limited period (2 days) over which the observations were taken, and because the study involved the use of an indirect method of current determination (dynamic height calculations and application of the geostrophic equations) which was deemed of questionable applicability in such restricted bodies of water as the arms of this bay. Likewise the drift bottle returns from the bay (Harrington, 1894) were insufficient for reliable interpretation of the current patterns of the bay.

Our present program in Grand Traverse Bay involves two distinct types of current measurement: Lagrangian and Eulerian. The Lagrangian measurements, utilizing several buoy and drogue techniques, will be described elsewhere. This report will describe the series of sub-surface current meter moorings installed in Grand Traverse Bay during the first 13 months (July 1970 - July 1971) of the integrated study of the bay, and some of the Eulerian measurements thus obtained.

Before commenting on the sub-surface moorings, an enumeration of the specific aspects of the circulation in the bay, which the sub-surface current meter mooring program is meant to illuminate, is in order. The current meter observations are intended to help describe:

(1) the wind-induced currents in the mixed surface layer (epilimnion);

(2) the extent of deep water (hypolimnion) circulation in the presence of a strong thermocline, and hence the extent of the coupling between the layers;

(3) the extent and nature of the circulation under the winter ice cover;

(4) the character of the exchange between the bay and open Lake Michigan, and hence the effective exchange rate, and;

(5) the magnitude of near-shore thermally-constrained jets, if present.

The five current meter moorings installed during the 1970-71 period covered by this report were intended to shed light on items 3 and 4 listed above, and, to a limited extent, item 1. Mooring A, installed at mid-depth in the upper end of the west arm of the bay (see Figure 1) in December 1970 and retrieved in April 1971, provided data for a period when the bay was covered by ice. Moorings B, C, D, and E, installed in the spring and summer of 1971 at several locations (see Figure 1) in the vicinity of the sill which is present at the mouth of the bay, were for gaining information on the nature of the oscillatory and transitory flow across the sill, i.e., on the exchange between the open lake and the bay.

This report will describe the two types of sub-surface buoys which were designed and constructed at The University of Michigan for use in the sub-surface moorings. It will also describe in detail each mooring, giving a narrative of the field work and including comments on instrument failures, handling problems, and so forth. The last section will present a summary of the data obtained from Moorings A and B.

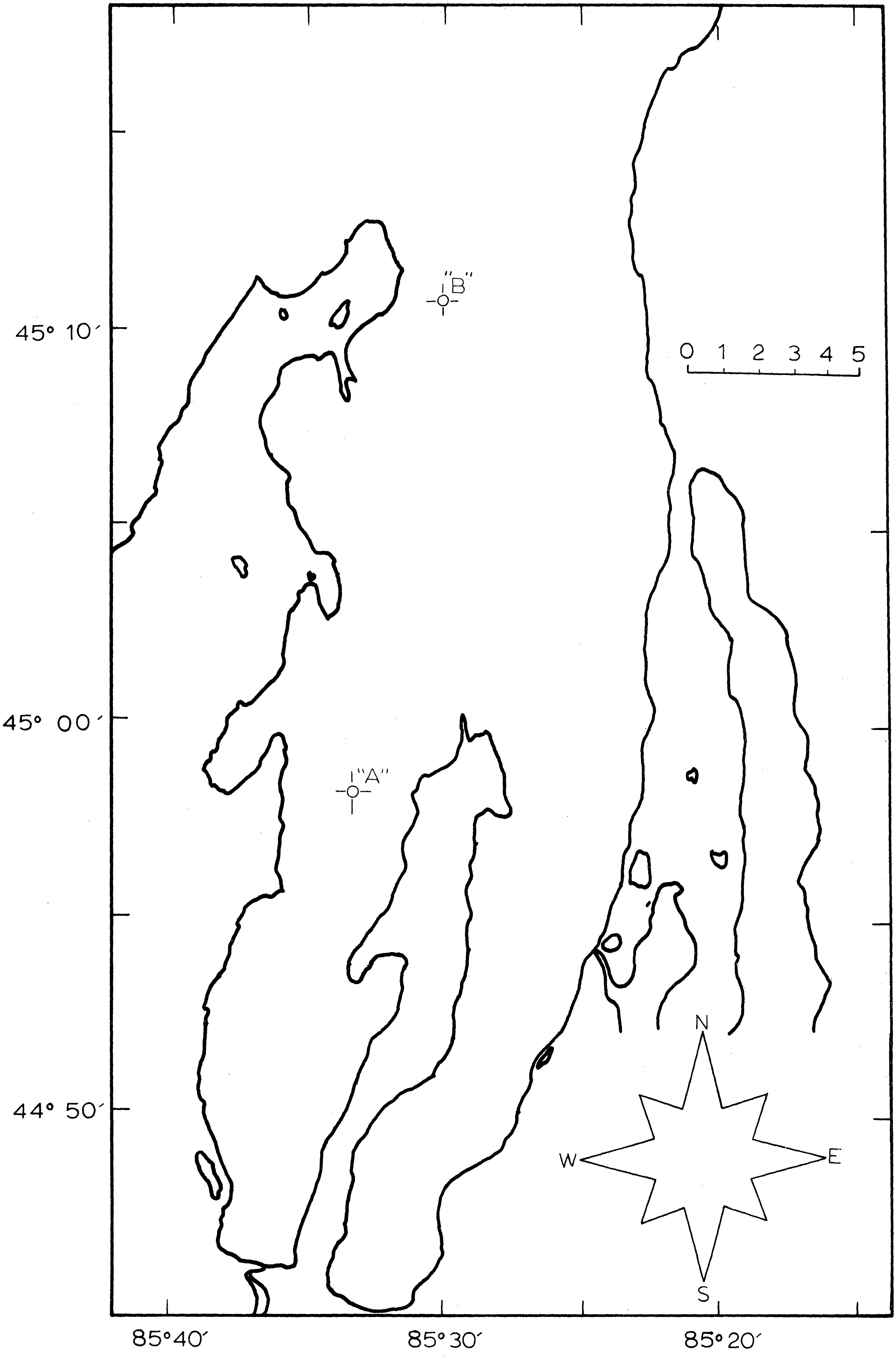


Figure 1 – Location of Current Meter Moorings in Grand Traverse Bay

SUB-SURFACE BUOYS

Sub-surface Float, First Design and Construction

Glass spheres, which characteristically become stronger at greater depths, are commonly used in deep ocean research and provide excellent buoyancy material, either by themselves in a fiberglass jacket or in an assembly with other materials. They do, however, represent a considerably greater expense to the scientist working in relatively shallow water than do other available buoyancy materials. The same argument applies to syntactic foam. Ready-made buoys such as "parabuoys," "planks on edge," torpedo-shaped steel buoys, etc., are available, but their cost generally exceeds by a large factor that of constructing a buoy specifically designed for use in shallow water.

By a process of elimination, it was decided to construct a buoy which would present a minimal cross-sectional area to current flow (thus reducing pressure drag) and yet be large enough to provide the desired buoyancy. The buoyancy material selected was polyurethane foam, which is formed in place by the mixing of two liquids. A rugged spine of 3/4-inch plywood was used as the backbone of the buoy, to which 26 plastic trawl floats were securely fastened. The inexpensive plastic floats can withstand the pressure at depths to 600 feet. The chosen design was in the shape of a frustrum of a cone having a hemispherical forward end. A large aluminum tail fin for orienting the "torpedo" into the current was attached to the buoy externally.

Because little was known about the currents in the area and the compressibility of the foam material with depth, a total net buoyancy of about 300 pounds was planned for the buoy. This would maintain the array in a near vertical attitude under maximal expected currents and provide a safety factor to offset buoyancy loss through compression of foam.

Actual construction consisted of attaching the small floats to the plywood spine to which a pipe support for the suspension of the instrument string had already been attached. This entire assembly was then placed in a two-piece, plastic-lined mold, around which the foam would be formed. The lower section of the mold was a large tapered metal refuse container; the upper section was of sheet metal attached to the lower section as a collar. The buoy was formed by pouring foam into the lower section of the mold; the collar was attached and the upper section of the mold was then filled with foam. In a matter of minutes, the foam had hardened sufficiently for the mold to be removed. After allowing time for the assembly to "cure," it was covered with fiberglass cloth and resin to provide a rather hard and durable finish to the outer surface. The buoy was then painted bright yellow with fluorescent Day-Glo stripes to make it more visible at a distance. Figure 2 shows the buoy being constructed, specifications are shown in Figure 3, and the completed buoy is shown in Figure 4.

Sub-surface Float, Second Design and Construction

Experience with, and field testing of, the first model revealed certain drawbacks. It was somewhat cumbersome and difficult to launch and retrieve and, because of compressibility, buoyancy decreased with depth. A heavy anchor was also required to counteract the buoyancy of the torpedo-shaped pod. Desirable operational characteristics included

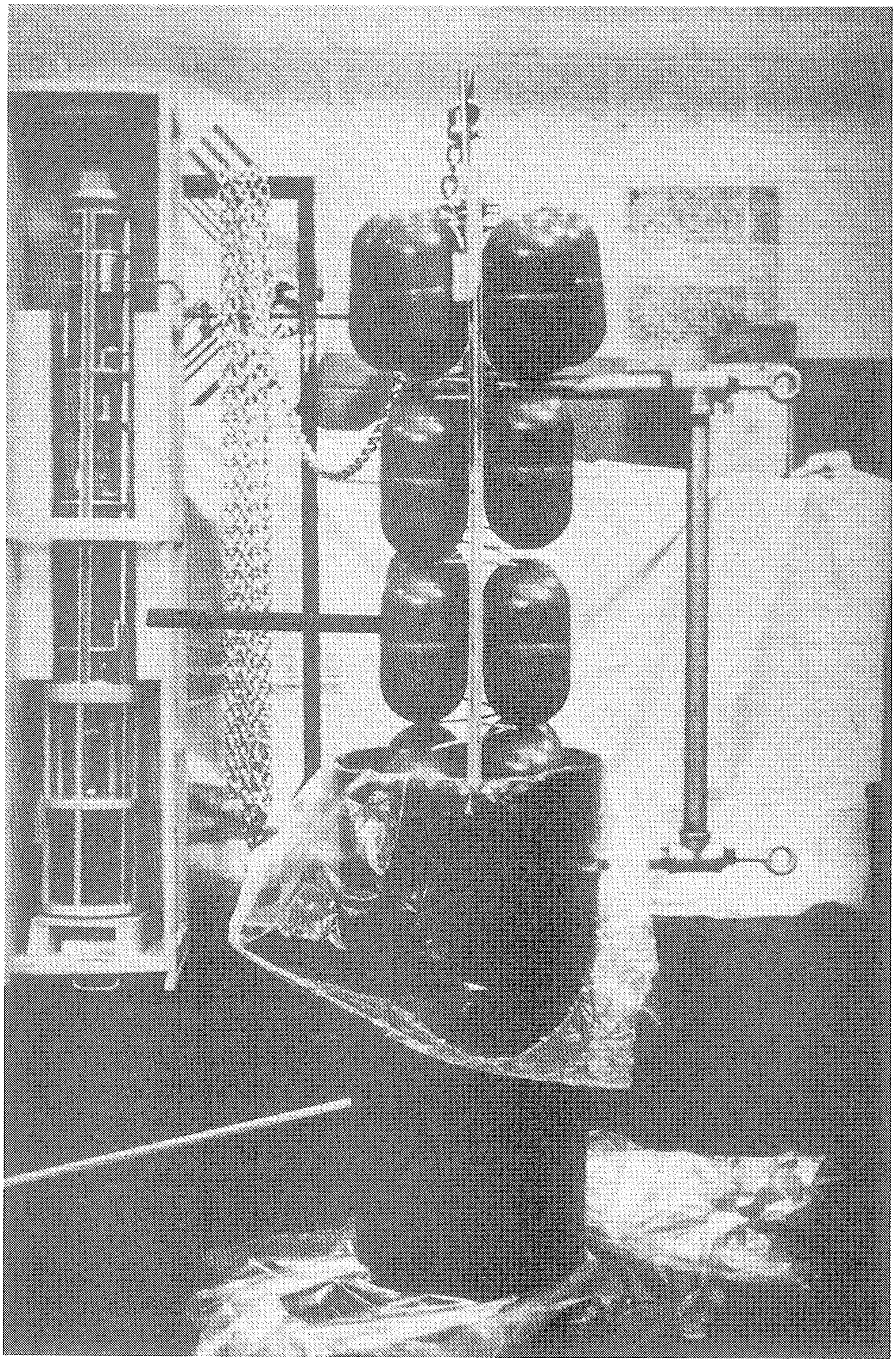
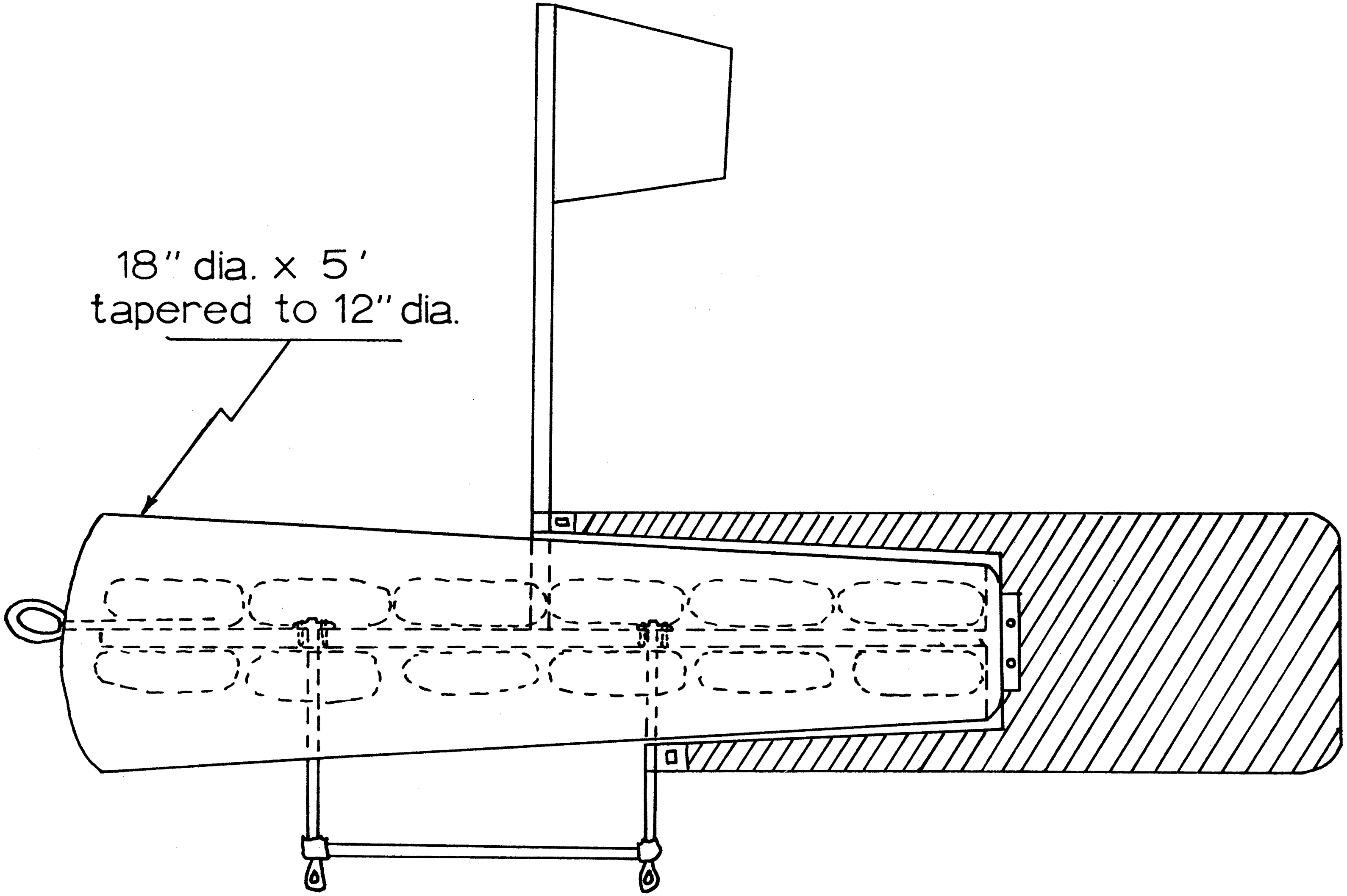


Figure 2. Polyurethane buoy: foaming process.



max. depth: undetermined
weight in air: 90 lbs.
net buoyancy: 380 lbs.
approx. construction cost: $160.

spine: 3/4" marine plywood
material: polyurethane foam
pipe support: 1" galvanized pipe
fin: 16 ga. alum. sheet

FIGURE 3 - POLYURETHANE BUOY: SPECIFICATIONS

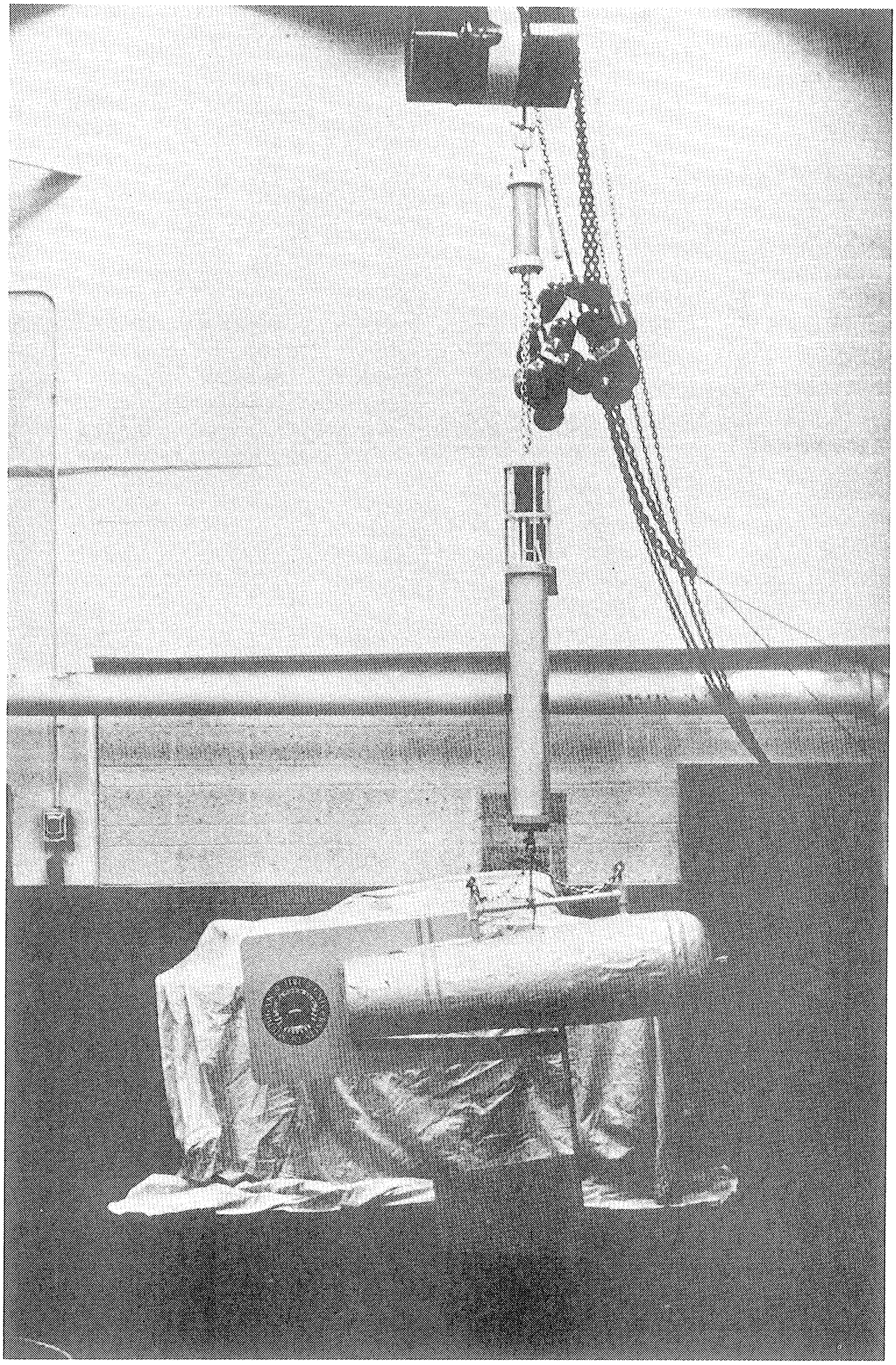


Figure 4. Polyurethane buoy: completed assembly.

(1) the development of an adjustable buoyant element that would provide sufficient lift to maintain the array of instruments within 5° of vertical and (2) a lighter anchor. Development of such an element would permit easier handling, and buoyancy could be matched to the instrument array and the current at the mooring site.

To meet the stated objectives, a self-orienting buoy was designed. The buoy was made up of a series of plastic trawl floats threaded on 3-foot lengths of thin wall conduit pipe; the conduit in turn was fastened to a metal frame by means of threaded rods. This assembly permitted addition or subtraction of floats as required by conditions. Thus, the buoy was dubbed SABA for Sub-surface Adjustable Buoyancy Assembly. Figure 5 shows the completed buoy with orienting fin, and specifications of the assembly are given in Figure 6.

Current meters used in this work did not contain inclinometers, therefore it was important that the mooring angle of the buoy be maintained within 5° of the vertical. Examination of the calibration charts for the Savonius Rotors for the current meters indicated that results would not be noticeably affected if the mooring angle were held within 5° of the vertical.

Procedures described by Fofonoff (1965) were used to determine deviation from the vertical for various buoyancy values and several instrument arrays. The procedure assumes that the inertial effects of the mooring are small in comparison to the horizontal drag and restoring force. Deviation values were calculated with a drag coefficient of 1.0, water density of 1.94 slugs/ft^3, and water speed of 1.0 foot/second. The values used were "worse case" conditions and therefore introduced a safety margin into the calculations.

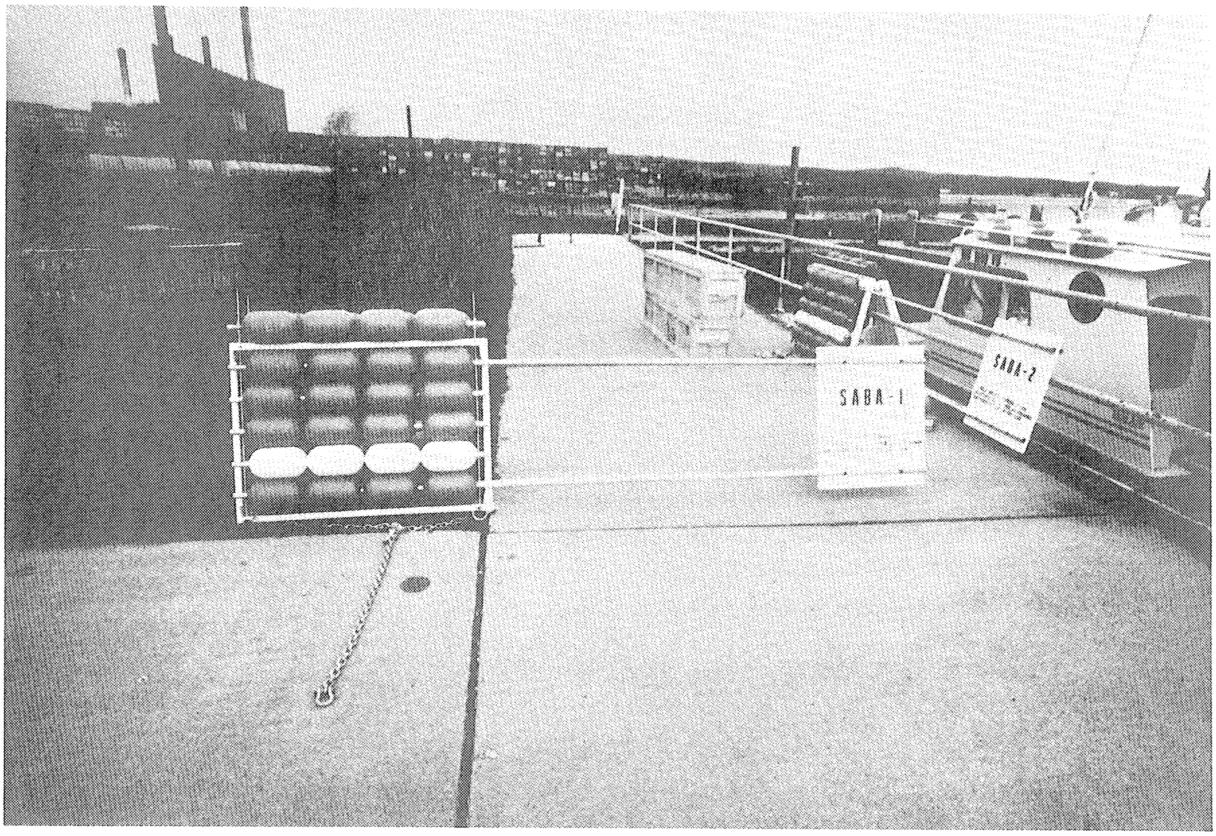
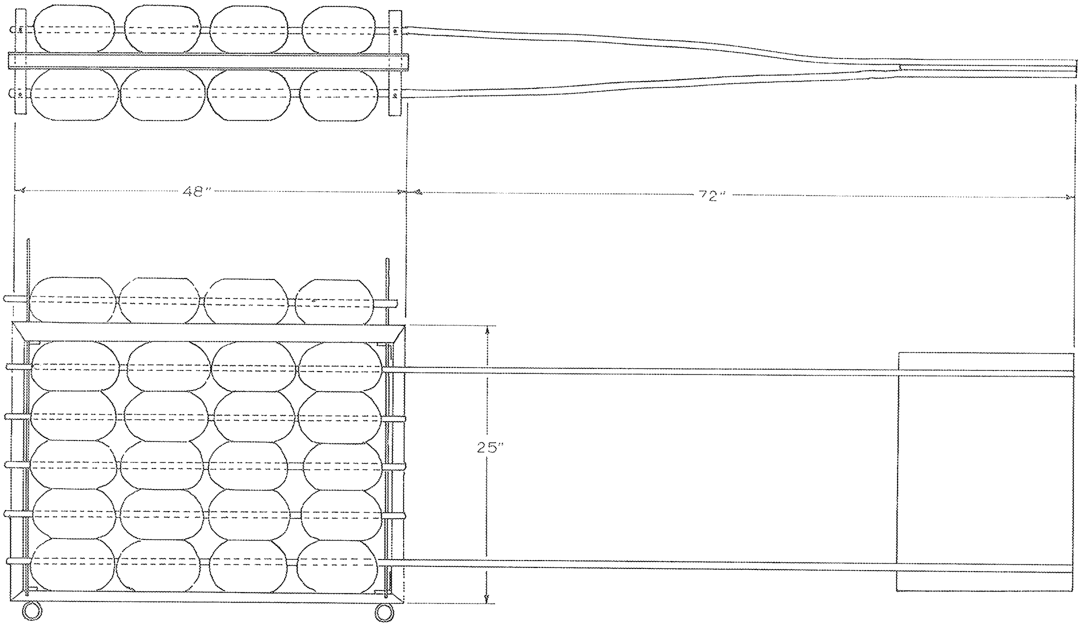


Figure 5. Sub-surface adjustable buoyancy assembly (SABA).

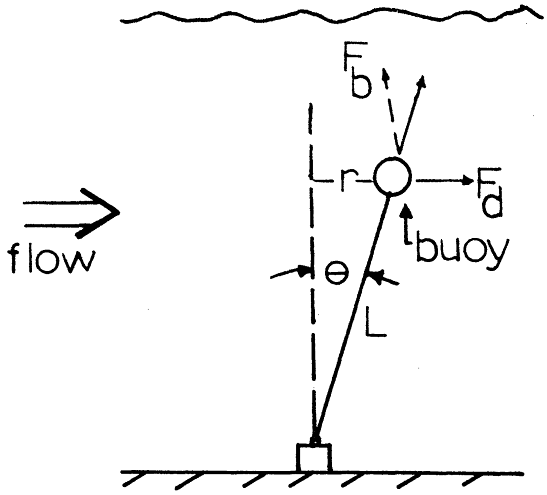


maximum depth: 600 ft.
weight in air: 60 lbs.
net buoyancy range 0 to 325 lbs.
approx. construction cost: $100.00

frame: 1/8" steel channel
floats: 5" dia. x 9" hollow plastic
float support: 3/4" thin wall conduit
fin: 3/8" painted marine plywood

FIGURE 6 - SUBSURFACE ADJUSTABLE BUOYANCY ASSEMBLY SPECIFICATIONS

The necessary calculations are given in Figure 7. Table 1 presents angles of deviation (θ) for various array lengths (L) and net buoyancy values (F_b). Note that for a given array length angle of deviation decreases with increased buoyancy; and that for a given buoyancy the angle of deviation increases as the length of the array increases. Thus, one must determine whether buoyancy or mooring length is the determining factor in a particular situation. In the Grand Traverse Bay cases, mooring length was the determining factor and the least possible buoyancy and anchor weight were sought such that the array would be held within the desired 5° of the vertical. For a mooring length of 70 feet, 100 pounds of net buoyancy in the SABA satisfied this criterion.



assume $F_d = F_r$

$F_d = (\rho C_d A V^2)/2$

$F_r = F_b r/L$

$\therefore \; \rho C_d A V^2 = 2 F_b r/L$

$\theta = \sin^{-1} F_d/F_b$

where:

F_d = horizontal drag force
F_r = horizontal restoring force
F_b = net buoyancy
ρ = water density

C_d = drag coefficient
A = total cross-sect. area
V = water speed
L = mooring length

FIGURE 7 - Drag Force Calculations

L (feet) \ F_b (lbs)	40	70	100	130	160	190	220
length neglected	θ(deg) 6.2	3.6	2.6	2.0	1.6	1.3	1.2
25	7.8	4.5	3.1	2.3	2.0	1.6	1.5
50	9.3	5.3	3.7	2.8	2.3	2.0	1.6
75	10.7	6.1	4.3	3.3	2.6	2.3	2.0
100	12.3	6.0	4.9	3.7	3.0	2.5	2.2

TABLE 1 - θ Vs F_b & L

CURRENT METER MOORINGS

Mooring A

45° 58' N
Latitude

85° 34' W
Longitude

Johnson
Set by

	hour	day	month	year
Set:	1200 EST	18	XII	70
Retrieved:	1730 EST	15	IV	71

Vessel: SEA GRANT I

Current meter: S/N 387, Model No. 102-0

Purpose

This first mooring was installed in the west arm of Grand Traverse Bay. The purpose was to determine some features of the winter circulation, particularly during periods of ice cover. The chosen location was in mid-bay off Merril Point on a bottom rise which ascends to within 100 feet of the water's surface. This rise extends laterally for about 1,000 feet along a northeast-southwest line and about 500 feet along a northwest-southeast line. The precise location is indicated on Figure 1 as "Mooring A."

Description

The features of this mooring are shown in Figure 8. Elements include: (a)* a fiberglass-covered, torpedo-shaped, polyurethane-foamed buoy, (b) a film recording current meter, (c) an auxiliary buoyancy pod, (d) an anchor release mechanism and line storage case, (e) a concrete anchor module, and several feet of 1/4" coil chain for chafing gear along with approximately 30 feet of 1/2" plaited nylon

*Letters correspond to key on Figure 8.

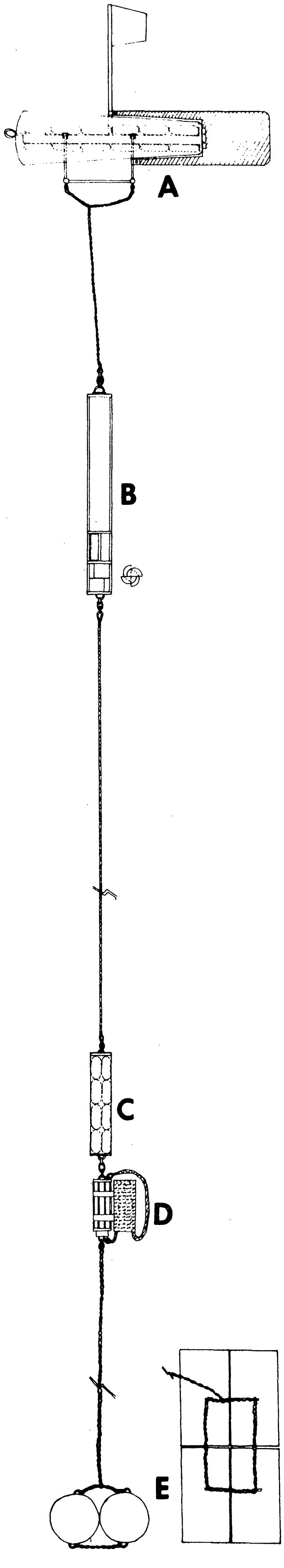


Figure 8. Mooring A: design.

line (Columbian rope) as the suspension element, and appropriate marine hardware for supporting each element within the array.

The (Geodyne Model 102) current meter digitally recorded current speed, along with vane and compass orientation, on 16 mm film at selectable time intervals. The anchor release mechanism was a time-release device (Geodyne Model A-855) which separated the array from the anchor module via an explosive piston arrangement. The line storage case containing 150 feet of 1/2" nylon line was fashioned from a two-gallon metal container, and the auxiliary buoyancy pod was made up of several trawl buoys having a total net lift of 72 pounds. The anchor was made of four thirty-gallon drums chained together, each filled with approximately 250 pounds of concrete, which left approximately half of each drum empty. This facilitated handling and permitted a quasi-controlled descent. Descent of the assembly was slowed by punching small holes in the empty half of the drums. These permitted a slow change of buoyancy with time as the air escaped and water leaked into the drum. Plaited nylon line was selected for the suspension element of the array because of its torque-free characteristics, tensile strength, elasticity under load, and proven open ocean use.

Narrative

Mooring A was designed to be emplaced with a minimum of effort from the research vessel SEA GRANT I (Figure 9). Once the mooring site had been located, surveyed, and the vessel anchored, the emplacement sequence was as follows: (1) The primary buoy was placed in the water with the current meter suspended directly beneath it via a three-foot length of chain. (2) The connecting nylon line, the auxiliary buoyancy pod, and the anchor release mechanism with attached line storage

Figure 9. Research vessel SEA GRANT I.

case were dropped. These elements were allowed to drift away from the side of the vessel to permit setting of the anchor without entangling the connecting line. (3) The four anchor drums were pushed to the deck's edge and, when all lines were clear, were easily pushed over the side. A light double line was looped through an eye of the primary buoy so that the final depth of the buoy and the current meter could be determined. This was done by allowing the line to descend with the buoy, marking both ends of the line at the water's surface, then pulling the line through the eye attached to the buoy. Thus the depth of the buoy was equal to 1/2 the distance between marks on the line. It was determined that the eye in the forward end of the buoy came to rest 45 feet below the surface and that the sensors of the current meter (savonius rotor and directional vane) were at a depth of 59 feet. The depth of the primary buoy is important because it had to be at least 40 feet below the surface so as not to interfere with commercial shipping and be unaffected by turbulence caused by vessels in close proximity. This measurement technique prevented errors resulting from fathometer inaccuracies, stretching of the nylon line, or the anchor sinking into the bottom.

At a predetermined time, the anchor release mechanism was to release the array from the anchor and allow it to ascend to the surface. The line storage case was to pay out its nylon tether line and maintain the array on station until it could be retrieved. The purpose of the auxiliary buoyancy pod was to bring the array to the surface should the line break and free the primary buoy from the rest of the array. The release mechanism functioned on schedule and the array ascended as planned. Due to an unexpectedly prolonged winter, the array ascended against the under surface of the ice and could not be recovered until twelve days later.

With the cooperation of the United States Coast Guard at Traverse City, the buoy was located at a position northeast of its original location some 15 feet below the water's surface. With the assistance of a scuba diver who severed the tether line below the anchor release mechanism, the entire array, minus the anchor, was retrieved in 215 feet of water. The primary buoy, the auxiliary pod, and scuba diver are shown in Figure 10.

It is theorized that the primary buoy or the protruding marker flag froze into the ice upon ascending, and consequently the entire array was dragged off its station into deeper water as the ice moved north. At a point when the downward acting force of the anchor weight on the now taut array exceeded the upward acting force from the ice grip, the buoy popped free, and as the line shortened under the reduced tension, the buoy sank to the depth at which it was subsequently found. Figure 11 shows the damage to the buoy, especially on its forward end, caused by ice, as well as the "circumferential squeeze" at its center which is believed to have been caused by water pressure during its time on station. The fiberglass cloth jacket had separated from the foam core over more than 50 per cent of the buoy, probably from inelastic compression of the foam. The overall weight of the buoy had increased by approximately 50 pounds, indicating absorption of water. The buoy's bright yellow color was largely responsible for its initial relocation, and facilitated aerial observation by the rescue aircraft of the U. S. Coast Guard. The other elements of the array were retrieved in satisfactory condition. The current meter provided completely valid data.

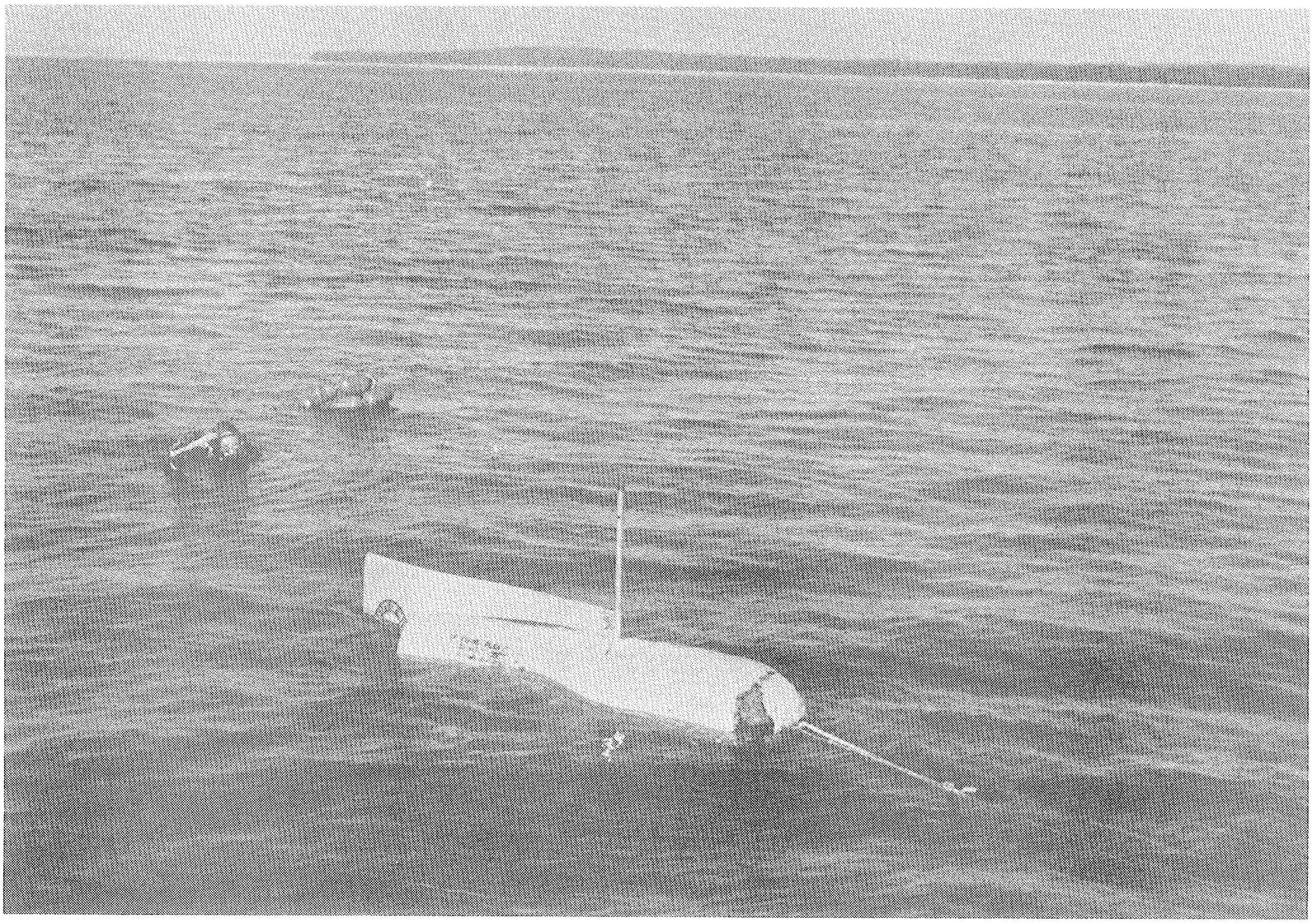


Figure 10. Mooring A: recovery.

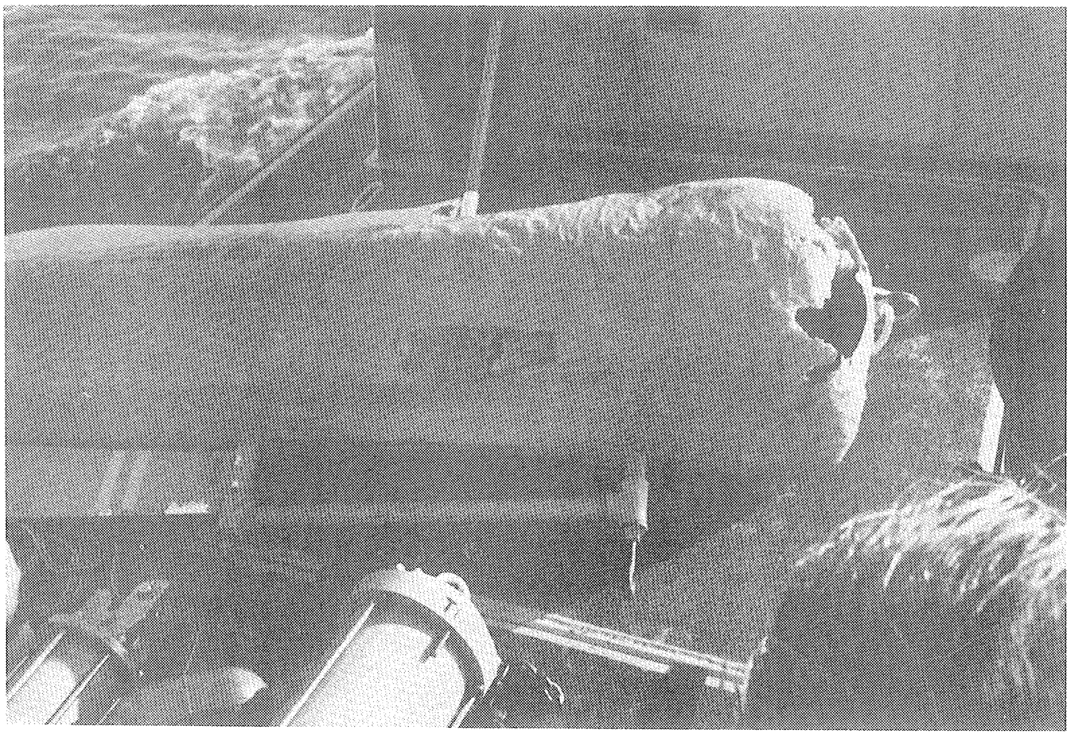


Figure 11. Polyurethane buoy: ice and pressure damage.

Remarks

From the damage to the primary buoy, it was decided that, for sub-surface buoys made largely of polyurethane foam, a sufficient safety factor could not be included in the design and still maintain an implantment procedure which could be easily conducted by a small research group and comparable vessel. In future winter moorings, the date when the release mechanism would function must include a larger safety factor to allow for variable duration of ice cover. Examination of the data revealed that the swivels (made of galvanized, unplated steel) did not function as intended and hence caused the current meter casing to rotate with the buoy as it was affected by currents. The data were unaffected, however. In the future, low-torque, lubricated swivels should be used.

Mooring B

45° 11' N
Latitude

85° 30' W
Longitude

Johnson
Set by

Set:	1450 EST	27	IV	71
	hour	day	month	year
Retrieved:	1530 EST	10	V	71
	hour	day	month	year

Vessel: SEA GRANT I

Current meter: S/N 263, Model No. 850

Purpose

This station was selected to collect measurements of sub-surface water motion over the west side of the sill near the mouth of Grand Traverse Bay. This mooring was set simultaneously with a similarly placed mooring on the east side of the sill 2.5 miles away. Information collected from this mooring was expected to furnish (1) insight into the open lake forces which affect circulation of Grand Traverse Bay, and (2) data on bay-lake exchange.

Description

The mooring is shown in Figure 12 and consists of the following elements: a sub-surface adjustable buoyancy assembly, a magnetic tape recording current meter (Geodyne Model 850), an anchor module, and an anchored surface marker tethered to the array by a 200 foot length of nylon line. One-half inch plaited nylon line served as the suspension element and standard marine hardware was used throughout. The anchor consisted of a single thirty-gallon drum filled with concrete. The surface marker was tautly moored and consisted of several large trawl floats threaded on a 3/4-inch thin-wall conduit pipe mast which had an

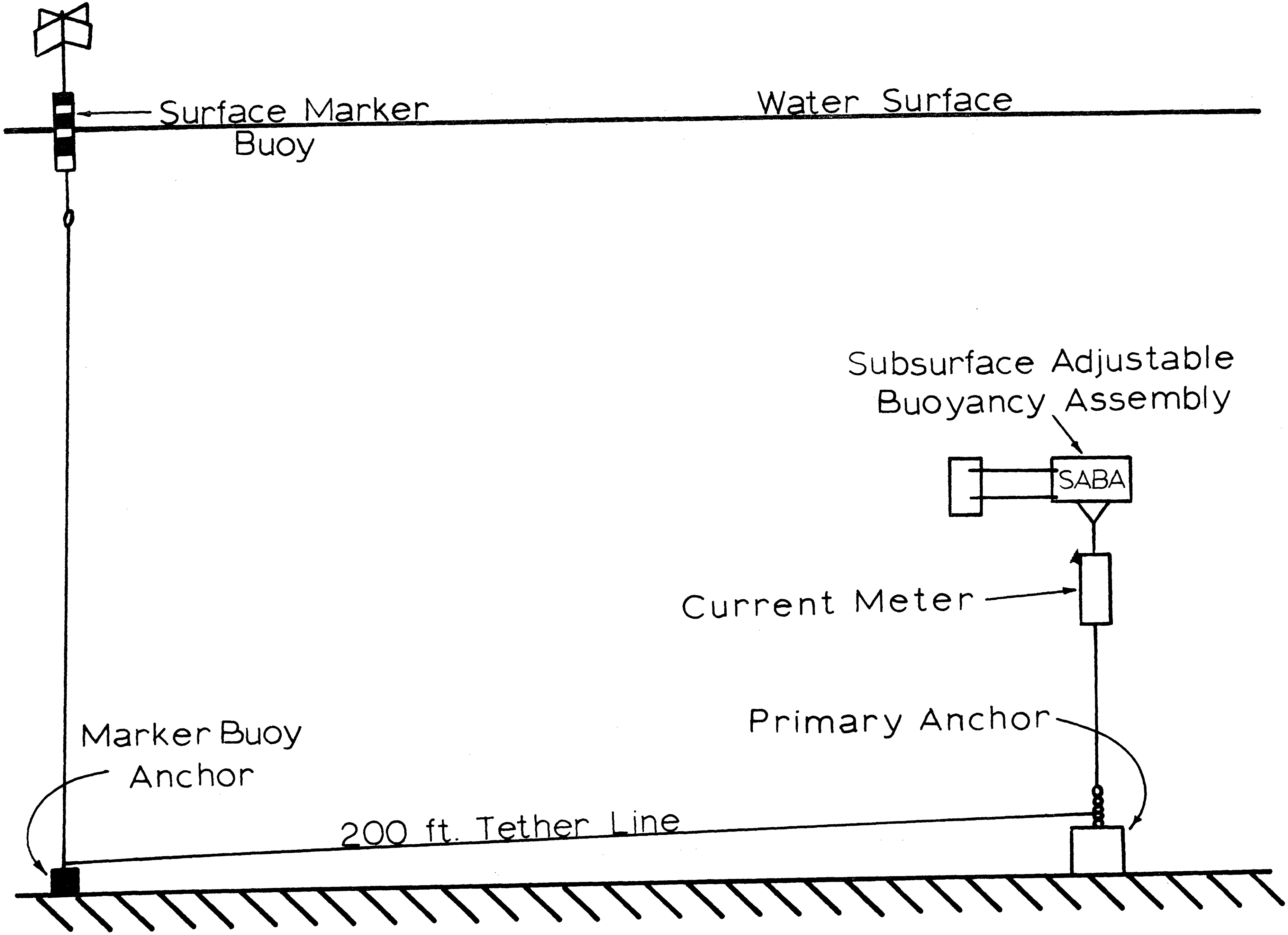


FIGURE 12 - MOORING "B" : DESIGN

aluminum radar reflector at its uppermost end with a fluorescent Day-Glo flag attached to the mast directly beneath the reflector. The marker was laterally separated from the array to avoid introduction of mooring motion, to facilitate descent on the array by scuba divers, to mark the location, and to provide a means by which the array could be relocated by dragging should the marker buoy become separated from its anchor.

Narrative

This mooring was placed with relative ease, in contrast to the setting of Mooring A. The marker buoy was first placed on station with its anchor, then 200 feet of nylon line payed out as the vessel moved away, and finally the primary buoy was placed. As before, the current meter was suspended beneath the SABA by a three-foot length of chain and this pair was allowed to drift away from the side of the vessel to allow for setting of the anchor without entanglement. Prior to pushing the anchor over the side, the vessel was anchored to avoid drifting from the station after emplacement. With all lines clear, the anchor was pushed over the side of the vessel without difficulty. Figure 13 is a photograph taken just prior to anchor setting and shows the SABA already in the water. Notice the surface marker, which was placed earlier, in the background.

This mooring was located in approximately 115 feet of water, and two scuba divers inspected the array *in situ*. The inspection took approximately fifteen minutes and was conducted by the University of Michigan "Underwater Operations" diving team. The pair of divers moved from the vessel to the surface marker, down the marker line to the anchor and across the tether line to the array. The array was inspected and the reverse procedure used for returning to the vessel. This avoided

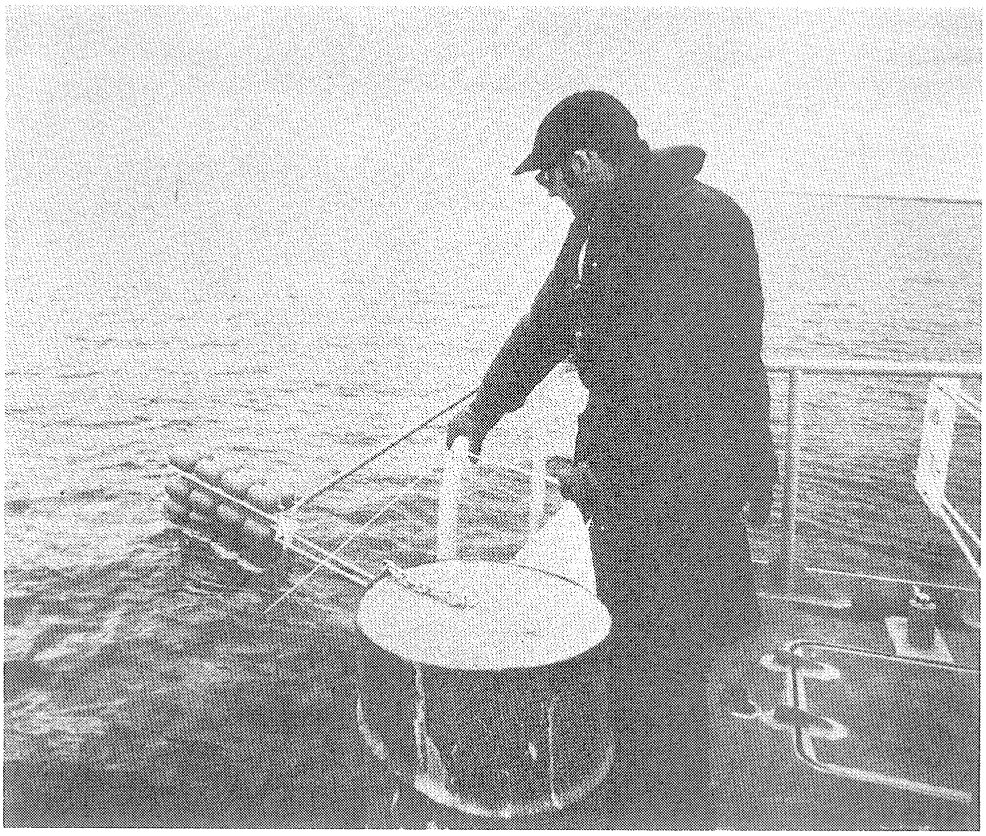


Figure 13. Mooring A: anchor setting.

the possibility of the divers not finding the array in the darkness, and provided everyone involved with a knowledge of exactly where the divers were at all times.

At the end of the data recording period a diver, using a tethered surface air supply, retrieved the current meter from the array without disturbing the mooring itself. Current meter removal was facilitated by placing extra pear-shaped rings within the instrument string to which a length of chain and a "come-along" could be attached. The current meter could then be bypassed by the chain and "come-along" and the in-line tension acting on the current meter removed. With a safety line attached from the vessel to the upper ring of the current meter, the connecting shackles at each end of the meter could be removed and the instrument allowed to swing free of the mooring. Figure 14 shows the diver removing the current meter. Note the nearly vertical length of chain to the left of the meter (the "meter by-pass" element) and the nylon safety line running off to the right. The diver is removing the upper connecting shackle just prior to letting the instrument swing free. It was then hauled to the surface and secured on board the vessel.

The diver for this work was specially outfitted with the following equipment: a complete dry suit (Unisuit of Sweden), a full face free-flow/demand mask (Aquadyne), a surface tethered air supply, hard wire communications with the surface vessel, and an emergency "bail-out" system in case of complete failure of the air supply system. This equipment provided the diver with maximum comfort, buoyancy control, ease of movement, and a high degree of safety.

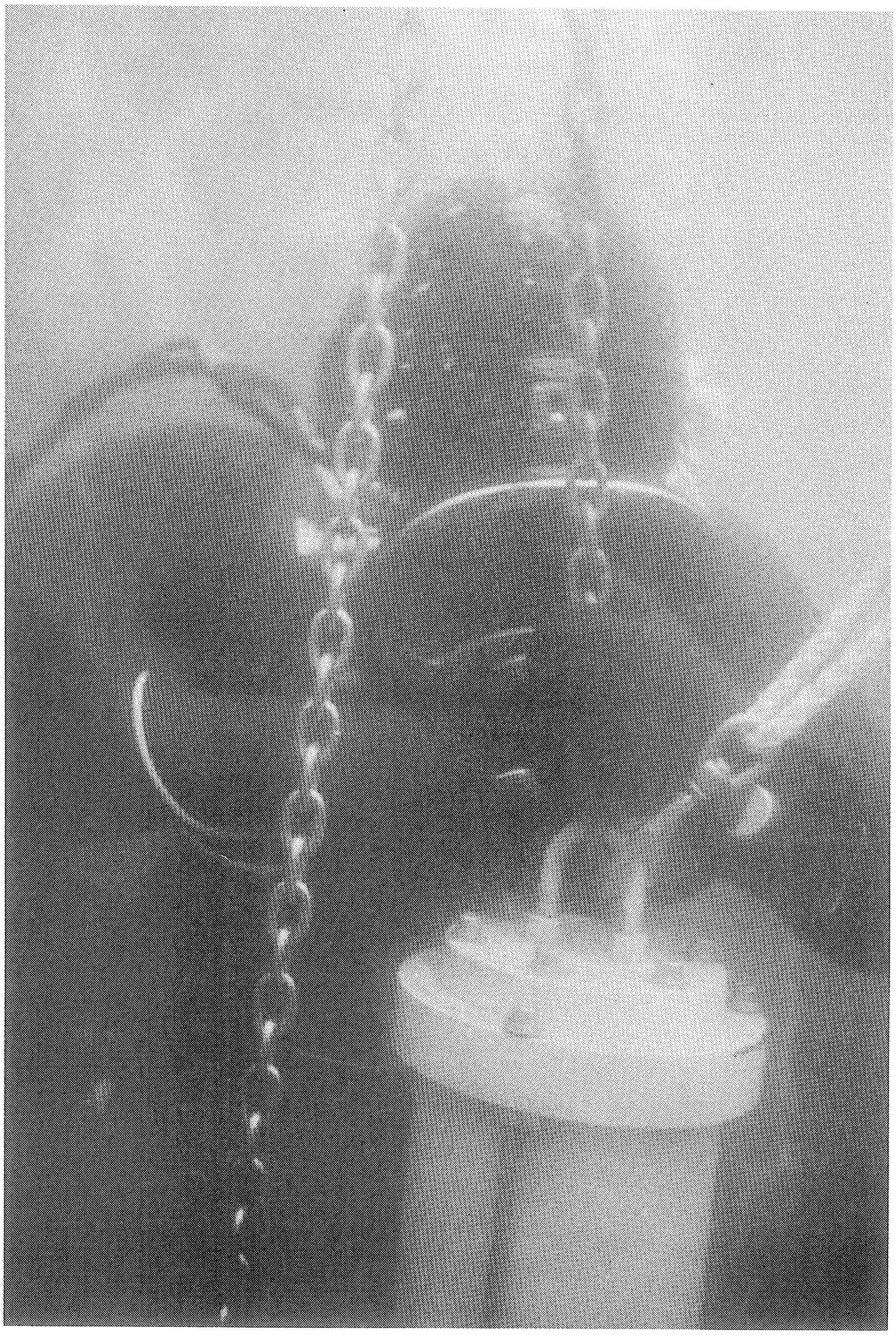


Figure 14. Meter extraction from sub-surface instrument array.

Remarks

Insofar as the techniques developed for servicing this mooring are concerned, the research group was very satisfied with the ease with which this operation was carried out. Relatively calm weather is necessary. The removal operation takes between 10 and 20 minutes, depending upon the skill of the diver. Direct voice communication with the diver proved extremely advantageous. Tools, etc., can be lowered via the safety line attached to the current meter as requested by the diver. A primary concern in the removal of the instrument from the array is safety to the diver and to the vessel should the suspension line break. A diver using SCUBA could remove the current meter, but not with the same degree of safety and ease. At least one scuba diver with extra air tanks was on the surface vessel at all times in the event of an emergency and to provide assistance if needed.

Mooring C

45° 12' N	Set:	1630 EST	27	IV	71
Latitude		hour	day	month	year
85° 27' W	Retrieved:	1400 EST	29	VI	71
Longitude		hour	day	month	year
Johnson	Vessel:	SEA GRANT I			
Set by					

Current meter: S/N 387, Model No. 102-0

Purpose

This station was selected to collect measurements of sub-surface water motion over the east side of the sill near the mouth of Grand Traverse Bay. This mooring was set simultaneously with a similarly placed mooring on the west side of the sill 2.5 miles away. Information collected from this mooring was expected to furnish (1) insight into the open lake forces which affect circulation of the Grand Traverse Bay, and (2) data on bay-lake exchange.

Description

The mooring is shown in Figure 12 and is identical to Mooring B. Water depth at this station was 80 feet.

Narrative

The entire operation was identical to that described for Mooring B.

Remarks

The mooring was emplaced and serviced utilizing the same techniques as developed for Mooring B. No difficulties were encountered during these procedures.

Mooring D

45° 11' N
Latitude

85° 30' W
Longitude

Johnson
Set by

Set: 1545 EST 10 V 71
hour day month year

Retrieved: 1240 EST 29 VI 71
hour day month year

Vessel: SEA GRANT I

Current meter: S/N 263, Model No. 850

Purpose

This station was identical to Mooring B and was chosen for the same reasons.

Description

Mooring D was identical to Mooring B.

Narrative

The mooring was as shown in Figure 12 and was identical to that of Mooring B. The mooring had already been established and it remained to replace the current meter. This operation was carried out by a surface supplied diver as described previously. The current meter was reinserted in the instrument array in the same manner as it was removed from Mooring B, except that the procedure was reversed.

Remarks

This was the first time that an instrument had been reinserted into an array after servicing, and the procedure was carried out without difficulty.

The technique that was developed to add or remove instruments from the array proved to be efficient, economical, and very worthwhile because it was not necessary to reset the entire mooring when successive measurements were made at one location.

Mooring E

45° 12' N	Set:	1350 EST	6	VII	71
Latitude		hour	day	month	year
85° 27' W	Retrieved:				
Longitude		hour	day	month	year
Johnson	Vessel:	SEA GRANT I			
Set by					

Current meter: S/N 263, Model No. 850

Purpose

This station was identical to that of Mooring C and was chosen for the same reasons.

Description

As shown in Figure 12, the mooring was identical with Mooring C.

Narrative

The mooring was serviced in the same manner described for Moorings B and D.

Remarks

While making other measurements in the area of Moorings C and D, it was noticed that, should the tether line between the main anchor and the anchor of the surface marker become snagged by a boat's anchor (or heavy duty fishing gear as is commonly used in this area), the surface marker could be moved from its original location into deeper or shallower water. The bottom topography in the area is quite irregular and depth may vary greatly within a few feet in any direction. The marker was tautly moored and not sufficiently buoyant to support the anchor if it were moved into deeper water. Therefore, it was decided to add a second marker which would serve two purposes: a surface marker would remain if the original marker should be dragged into deeper water and additional identification of the mooring would be provided. This white extra buoy carried the following black lettering: Sea Grant Circulation Project, Department of Meteorology and Oceanography, The University of Michigan, Ann Arbor, Michigan, and the telephone number of the main office. It was made of fiberglass-covered polyurethane, was about three feet long, and had a volume of approximately one cubic foot. The second marker was in fact helpful in locating the station. One week after the termination of Moorings C and D, while proceeding back to the two stations to place meters for Moorings E and F, neither of the two markers were observed at what had previously been Mooring D (west side of the sill). Consequently, this station was temporarily set aside and the group proceeded onto what had been Mooring C (east side of the sill). At this station, only the white cylindrical buoy was found and the initially placed marker with radar reflector was missing. A close examination of the line which had connected the marker to the anchor, clearly revealed that the 1/8" steel cable (more than sufficient for this use) had been cut with wire cutters or another sharp instrument. No fraying or wear had occurred to any of the lines. The current meter was then inserted in the array according to schedule and the vessel returned to port.

That evening the missing marker buoy was returned by a fisherman who had picked it out of the water some 6 miles north of its moored location. On 9 July, three days after the placement of Mooring E, an attempt was made to locate the surface marker from a shore vantage point using high powered binoculars and a theodolite. The search on the afternoon of the 9th and all day on the 10th for the surface marker proved fruitless, and the use of a surface vessel was called for. On 13 July, a hasty search from a small Boston Whaler was to no avail. Rough weather prevented a more thorough search.

During the next 7 weeks, 12 separate attempts were made to locate the mooring: first, by dragging a single grappling hook; second, by towing a weighted line between two boats; and finally, using a 200 kilohertz side-scanning sonar. In all, approximately 330 man hours were expended, 116 while using two vessels, 126 with the sonar, and the remainder with one vessel during dragging operations or visual search for the marker. Admittedly, as the search progressed, techniques improved. By the time the search operations terminated, the group had developed efficient techniques for the use of side-scanning sonar and shore-based theodolite stations from which the search vessel's position could be accurately located by triangulation. The sonar search was conducted in cooperation with a team of scientists from the Geophysical and Polar Research Center at the University of Wisconsin, Madison. This phase of the search, as described by Clay (1971), has provided three possible locations for Mooring E, one location being of particular interest in that the interpretation of the sonar trace indicated an object of the same relative size and height above bottom as that of the current meter. Time has not yet permitted these three areas to be further investigated, but it is hoped this can be undertaken in the near future.

DATA SUMMARY - PRELIMINARY RESULTS

The data obtained from the current meters can be manipulated in many ways. We have chosen to follow the methods described by Webster (1964) for the analysis of a long time series of current meter observations. Following is a brief presentation of the data thus far analyzed from Moorings A and B.

Mooring A

Data ID: 401406

Record Begins: 0 18 XII 70 EST
hour day month year

C.M. S/N: 387

Record Duration: 97 1 0
day hours minutes

C.M. Depth: 18 meters

Sampling Interval: (see comments)

Water Depth: 30.5 meters

Magnetic Variation: (not included)

Comments on Results

The current meter functioned properly throughout the entire recording period. Thirty-one samples, spaced 5 seconds apart, of each of the 3 variables (compass, vane, speed) were recorded in each 2.5 minute "on" period. Each "on" period was followed by a 12.5 minute "off" period, thus completing the meter's 15-minute cycle. This permitted direction to be computed by vectorially adding the vane (the angle of the deflection vane with respect to the instrument case) and compass (the angle of the instrument case with respect to magnetic north) components. Figure 15 is a bar plot of frequency of occurrence of each possible value of direction and is called a direction histogram. One hundred twenty-eight class intervals (e.g., 0°, 3°, 6°, etc.) of direction were used which correspond to the current meter's 7 channel Gray binary encoding disc divisions. The left portion of the plot is a graphical representation of direction in which the length of each bar reflects the quantity of observations for that class interval, the column adjacent and to the right of this portion contains the number of observations occurring in each class, and the rightmost column contains the angle in degrees (magnetic) of that class interval. Notice that the primary mode resides at 264° magnetic, while the average direction was 201.26° magnetic.

Figure 16 is a bar plot of frequency of occurrence of each possible value of speed and is consequently called a speed histogram. The interval is 1 cm/sec. as listed in the right-hand column. The primary mode resides at .5 cm/sec. and the average speed is 3.55 cm/sec. No speed greater than 20.5 cm/sec. was recorded.

If the raw data are partitioned into uniform time intervals and a speed and direction histogram are determined for each interval, these histograms may then be plotted against real time (in steps of the chosen time interval) to construct a time histogram. The time histogram is a record of the current meter observations, in the form of a series of short time interval histograms (in symbolic form), which provides a comprehensive picture of current speed and direction in a rather concise manner.

Figure 17 is a time histogram of the observations recorded during Mooring A. The left portion contains the direction data and is scaled from zero to 360 degrees, left to right. The center column is the sequence number which is read in digit pairs as day, hour, and minutes. The right-hand portion contains the speed data and is scaled from 0 to 200 mm/sec. from left to right. The symbol (@) represents that angle or speed which has the greatest frequency of occurrence, the symbols 1, 2, 3, etc., represent those values which occur with a frequency of 10%, 20%, 30%, etc., of that which is represented by (@). The symbol (.) represents those values which occur with a frequency of less than 10% of that represented by (@). Only the first eight days of the current meter observations are presented in this form as an example of the comprehensiveness of the time histogram.

The velocity vector averages for each time segment as listed on a North-East Velocity Component Diagram (to be discussed under Mooring B) can be used to obtain a graphical presentation of the current meter data.

By multiplying a velocity value by the elapsed time since the previous multiplication operation (i.e., the value of the time interval) a velocity vector displacement can be determined. If one is to add serially each of the resultant displacements to that previously determined, a series of displacements will be obtained which will begin with time zero and resemble, but is not to be confused with, the horizontal projection of a water particle trajectory with time.

Figure 18 is the result of performing the above-described operation and is commonly called a progressive vector diagram or "Provec." The "curve" has been constructed by connecting points which represent a single value of vector displacement and are separated by 900 seconds of real time. The record begins at the asterisk on 18 December and concludes on 25 March. The days are labeled every third day and are noted on the curve with a cross. The spatial scale of the diagram corresponds to the displacement which would occur if the motion over the entire area (i.e., the extent of the displacement diagram) were the same as observed at the location of the current meter. It is important to note that this rarely happens in real situations.

To assist with the understanding of this diagram, imagine the "curve" to be a water trough with the asterisk in the upper right-hand corner being a source of water. If the water were made to flow through the trough and exit at the lower left-hand corner, one could determine the direction of water travel past the current meter for a particular moment in time simply by observing the direction of flow in the trough at the time of interest with respect to magnetic north. For example, between 30 December and 2 January, the flow was essentially southward. The distance between the cross labeled 30 and the cross labeled 2 on

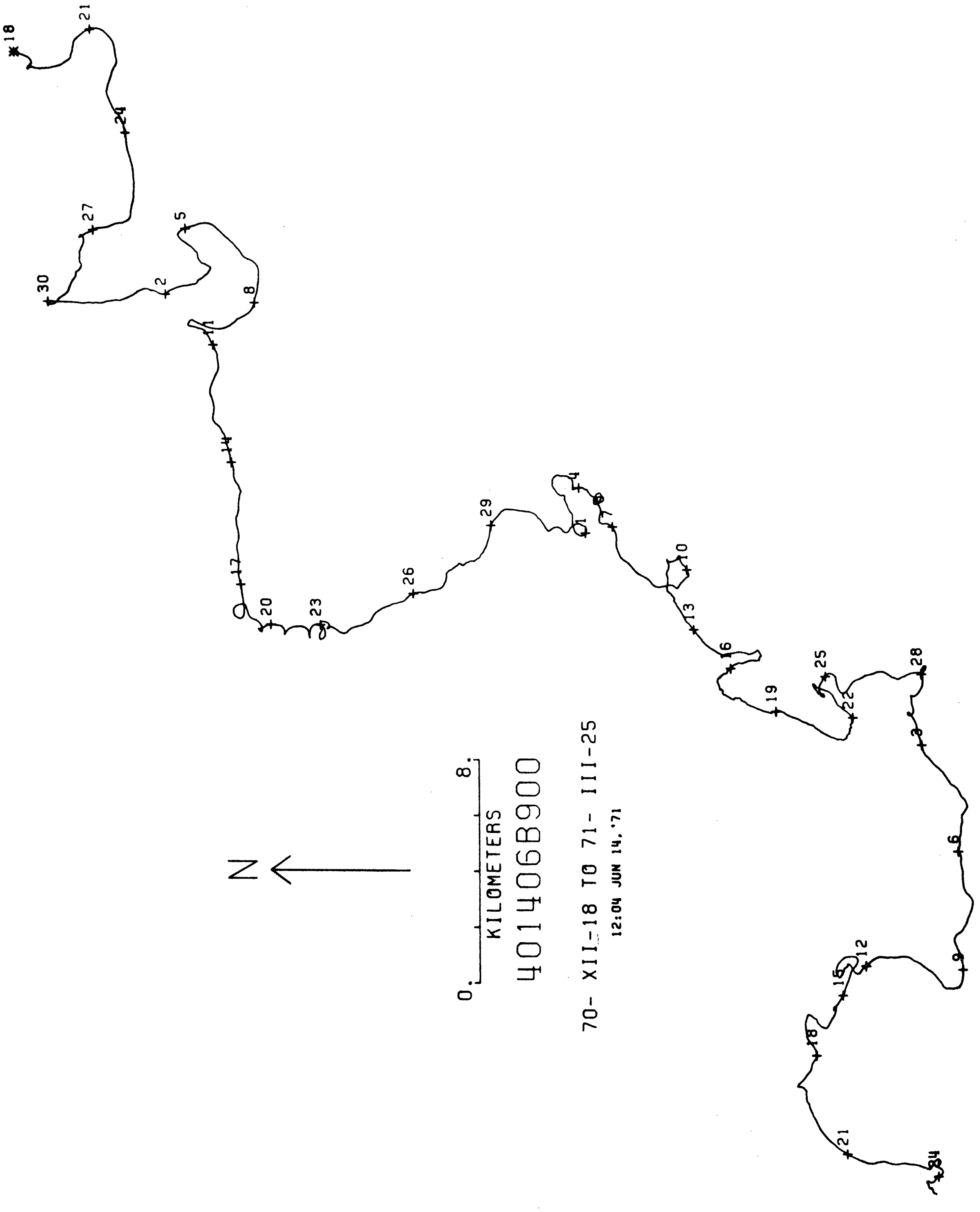


Figure 18. Progressive vector diagram: Mooring A.

on the diagram is an indication of the distance water traveled past the current meter during this 3-day interval. The net virtual displacement of water past the current meter during the 97-day measurement period was 52.80 kilometers. The net west displacement was 41.16 kilometers and the net south displacement was 34.51 km. Consequently, the flow has been south and west past the current meter. Notice the clockwise rotary flow experienced between 17 and 23 January. The period of this motion is approximately one day.

Mooring B

Data ID: B850

Record Begins: 14:56 27 IV 71 EST
hour day month year

C.M. S/N: 263

Record Duration: 8 14 53
days hours minutes

C.M. Depth: 18.3 meters

Sampling Interval: (see comments)

Water Depth: 35.1 meters

Magnetic Variation: 2° West

Comments on Results

The current meter functioned normally throughout most of the recording period. Thirty-one samples of compass, vane, and speed were recorded every 160 seconds with 5 seconds between samples (continuous mode).

Figure 19 is a direction histogram of the data collected as a result of Mooring B which indicates approximately 3 modes, one each at 11°, 197°, and 349°. The average direction of water movement was 171.02°. The apparent lack of any recorded values at 138°, 166°, 194°, and 222° has not been explained, but is likely a result of mechanical encoding problems within the meter itself.

Figure 20 is a speed histogram for these data. Notice that no speeds higher than 17.5 cm/sec. were recorded and that the most frequently encountered speed was 1.5 cm/sec. The average speed for the measurement interval was 3.07 cm/sec.

Figure 21 is a time histogram for the period. Notice that there were essentially only three major time periods during which the most frequently recorded speed was not zero. Additionally, during that time interval when the predominantly recorded speed was zero, the spread of direction almost always was greater than when the greatest occurring speed was not zero as might be expected, because at low speeds the directional vane tends to wander.

The histogram presents direction and speed components in polar form from which velocity may be determined. An alternate method, in Cartesian form, may be used for describing current meter observations in the form of north and east velocity component diagrams. The vector addition of the north and east components enables one to determine the current velocity at any given time. A plot of each of these components enables one to view general trends in the flow more easily than by the histogram method.

Figure 22 is a north-east velocity component diagram of the data collected using Mooring B. Here, the values of the north and east components are average values taken over a uniform time interval for the entire data record. This permits compaction of the plot into a smaller size and smooths the curve. The Cartesian expression of average velocity has the advantage of eliminating back-and-forth mooring motion as a result of opposite velocity components cancelling out. In Figure 22 the north-south component of velocity shows a distinctly greater amount of oscillation than that of the east-west component.

If Figure 22 is compared with Figure 23, which is a progressive vector diagram of the same data record, one may see the large north-south amplitude of oscillation more clearly. By comparing the data for the time period of 2 to 3 May, the correlation between the progressive vector diagram and the north-east component diagram is clear. The progressive vector diagram especially permits a better physical understanding of the flow over a given time period. The net virtual displacement as seen in Figure 23 was 2.1 km. The net east displacement was 1.19 km and the net north displacement was 1.79 km. Consequently, the net flow at the location of Mooring B was north and east during the eight-day measurement period.

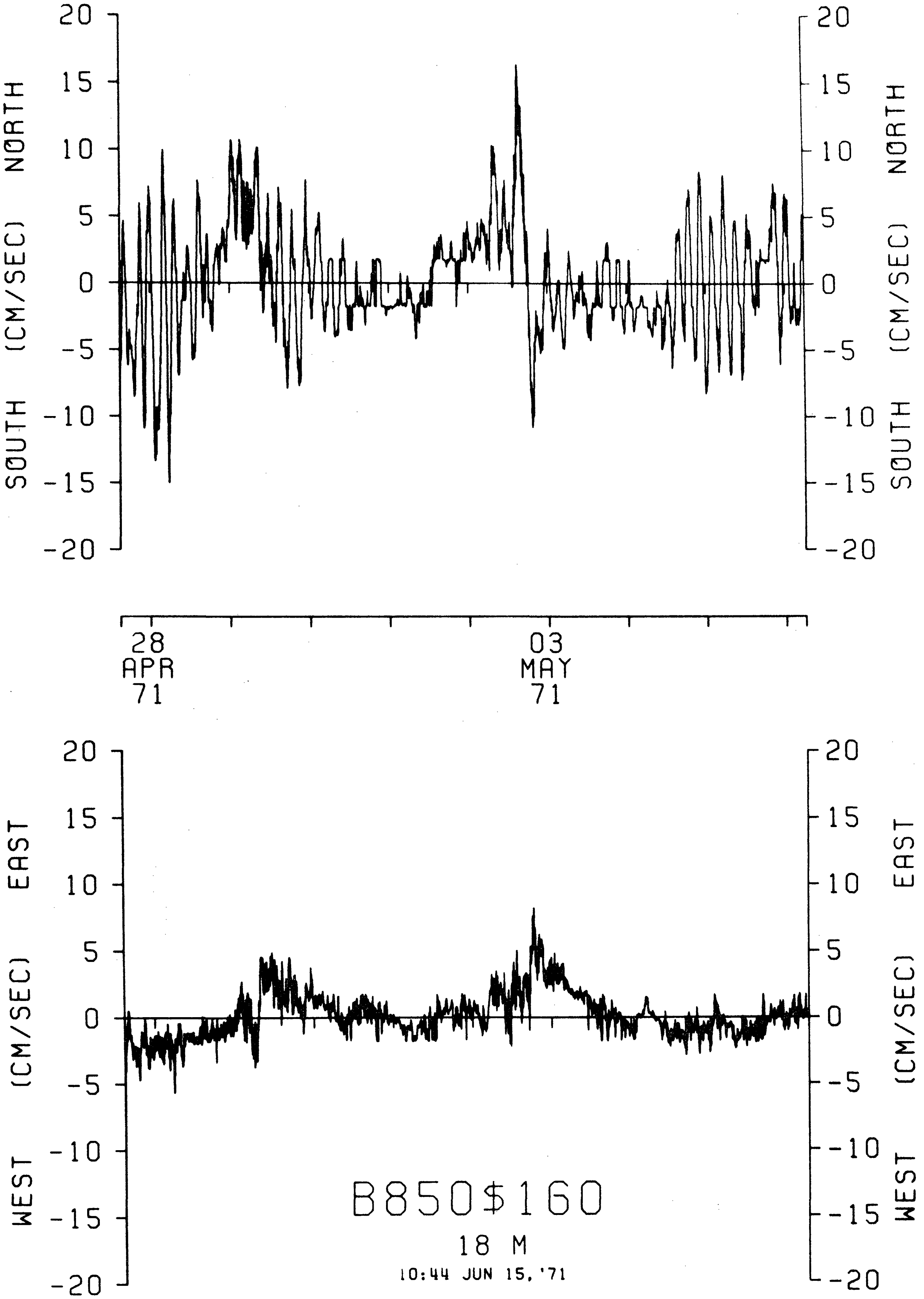


Figure 22. North-east velocity component diagram: Mooring B.

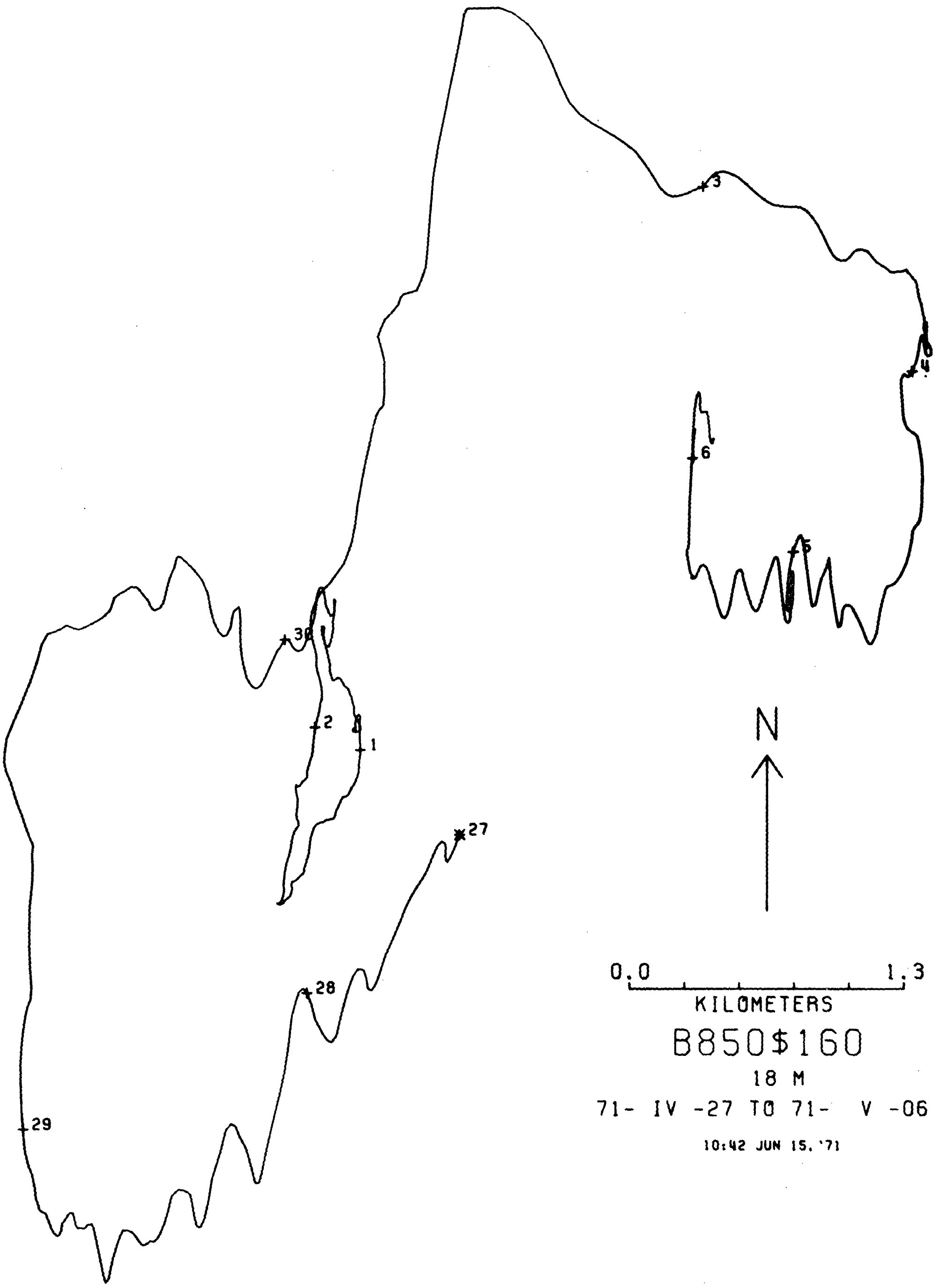


Figure 23. Progressive vector diagram: Mooring B.

REFERENCES

[1] Clay, C. S. 1971. "Side Looking Sonar Search in Grant Traverse Bay, 25-29 August 1971," Internal Report, Geophysical and Polar Research Center, University of Wisconsin, Madison.

[2] Fofonoff, N. P. 1965. "A Technique for Analyzing Buoy System Motion," Geo-Marine Technology, 1 (7): 10.

[3] Goldman, G. C. 1971. "Surface Meteorological and Oceanographic Platform," Technical Report, Department of Meteorology and Oceanography, The University of Michigan, Ann Arbor.

[4] Harrington, M. W. 1895. "The Surface Currents of the Great Lakes," U.S. Weather Bureau, Bulletin B.

[5] Lauff, G. H. 1957. "Some Aspects of the Physical Limnology of Grand Traverse Bay," Great Lakes Research Institute, Pub. No. 2.

[6] Webster, F. 1964. "Processing Moored Current Meter Data," W.H.O.I. Technical Report, 64-55, unpublished manuscript.

[7] Webster, F. 1968. "A Scheme for Sampling Deep-Sea Currents from Moored Buoys," W.H.O.I. Technical Report, 68-2, unpublished manuscript.