AN ABSTRACT OF THE THESIS OF

Paul McAlpine Maughan for the Master of Science in Oceanography.

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Title OBSERVATIONS AND ANALYSIS OF OCEAN CURRENTS ABOVE 250 METERS OFF THE OREGON COAST.

Abstract approved Redacted for Privacy

Observations of current flow to 1000 meters below the sea surface at 50 miles off Newport, Oregon, were made with the aid of parachute drogues. Data was collected during six 1962 cruises. Analysis of current structure above 250 meters shows:

1. Surface currents predominately flow northerly from November to March and southerly from April to October. A significant portion of the flow is on-shore except during July when a definite off-shore component is found.

2. Currents from the surface to 50 meters are geostrophic.

3. Below 50 meters and above 150 meters a discontinuity layer appears. The minimum velocity usually occurs in this layer. The flow shows greater non-geostrophic characteristics as the 100 meter level is approached.

4. Below approximately 100 meters and above 250 meters the flow is non-geostrophic.

OBSERVATIONS AND ANALYSIS OF OCEAN CURRENTS ABOVE 250 METERS OFF THE OREGON COAST

by

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OBSERVATIONS AND ANALYSIS OF OCEAN CURRENTS ABOVE 250 METERS OFF THE OREGON COAST

I. Introduction

The major current that affects the Oregon coast is the California current, a portion of the eastern current gyrel in the North Pacific Ocean. This flows all year from north to south.

During the spring and early summer months north to north-west winds prevail off the coast of Oregon. These give rise to upwelling that most frequently begins in June and continues until early fall. According to Sverdrup, Johnson, and Fleming (15, p. 725) during the entire season of upwelling, a countercurrent that contains considerable quantities of Equatorial water flows close to the coast at depths below 200 meters. In the fall the upwelling ceases and in the surface layers a current opposite to the direction of the California current develops, the Davidson current which in November, December, and January runs north along the coast to at least latitude 48° North.

These statements pertain specifically to the California coast, and to average or prevailing conditions. Details of the circulation off Oregon, and the variability from year to year, or even month to month, have not yet been investigated.

With the implementation of the R.V. Acona[1], it became possible to examine the reliability of the earlier qualitative and statistical summaries (15, Chart VII, 19, Chart 15) with detailed quantitative measurements. A series of cruises off the Oregon coast were planned to measure directly the current structure to a depth of 1000 meters. This paper represents a summary of the first year's work on the project, including a summary of the methods of observation and reduction of data and an analysis of the current measurements obtained.

Background and History

Ocean currents have been studied extensively by oceanographers for many years. The first knowledge of oceanic currents came from ship's drift. Later, the work in this field appeared to be concerned primarily with large-scale movements of water masses in the oceans of the world. This work was, however, concentrated on the surface current systems and mass transport in the upper layers, and not until recently has any extensive investigation on currents below the surface been attempted.

Early attempts at subsurface current measurements have given us accounts such as found in Maury's book, Physical Geography of the Sea (11, p. 169). He states:

A block of wood was leaded to sinking, and, by means of a

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[1] R.V. Acona - Research vessel operated by the Department of Oceanography, Oregon State University.

fishing-line or a bit of twine, let down to the depth of one hundred or five hundred fathoms, at the will of the experimenter. A small barrel as a float, just sufficient to keep the block from sinking farther, was then tied to the line, and whole let from the boat. To use their own expressions, 'It was wonderful, indeed, to see the barrega move off, against wind, and sea, and surface current, at the rate of over one knot an hour, as was generally the case, and on one occasion as much as 1 3/4 knots.' The men in the boat could not repress exclamation of surprise, for it really appeared as if some monster of the deep had hold of the weight below, and was walking off with it. Both officers and men were amazed at the sight.

In recent years considerable work has been done on the fine structure of ocean currents in both deep and shallow water. A selected list of some of the investigations since 1954 are shown in table (1).

Investigator(s)	Publication Reference #	Page Number(s)	Year of Publ.	Current System Studied
Cromwell, Montgomery and Stroup	3	648-649	1954	Pacific Equatorial undercurrent
Swallow	16	74-81	1955	Vicinity 15°W, 41°N
Pickard	12	581-590	1956	Strait of Georgia current
Swallow	17	93-104	1957	Vicinity 0°W, 63°N and 15°W, 35°N
Jennings and Schwartzlose	6	42-47	1958	California Current
Stommel	14	1-202	1958	Gulf Stream
Knauss and Pepin	8	380	1959	Pacific Equatorial countercurrent
Knauss	9	265-286	1960	Cromwell current
Knauss	10	143-155	1961	Pacific Equatorial countercurrent
Wooster and Gilmartin	22	97-122	1961	Peru Chile undercurrent
Reid	13	134-137	1962	California countercurrent

Table (1). Selected investigations of ocean current systems since 1954.

To date, very little of the deep ocean has been studied. Only a relatively few subsurface current measurements have been taken, and these measurements have been largely confined to the major current systems of the oceans.

The measurement of currents can be carried out either by indirect or direct methods.

The indirect methods require the use of assumptions concerning the type of flow one is measuring. For example, if one can be sure that all flow is horizontal, unaccelerated and frictionless, measurement of sea surface slope is all that is required for computation of the surface current. This particular procedure, widely used in oceanography, will be discussed in some detail in section III, the geostrophic approximation.

There are two methods of direct current measurements. The "flow" or Euler method observes the speed and direction of flow at a fixed point as the particles pass. The "float" or Lagrange method of attack follows the drift of an object that one assumes is flowing with the water during its motion through space.

The block diagram, shown in figure (1), shows the various methods whereby current velocities are determined.

The actual devices used fall into three categories: 1. rotating element current meters (flow type), 2. drift type current measuring systems (float type), or 3. miscellaneous types of current meters.

The first type of current meter can be distinguished either by a propeller or cup and/or paddle wheel. Several of the most common

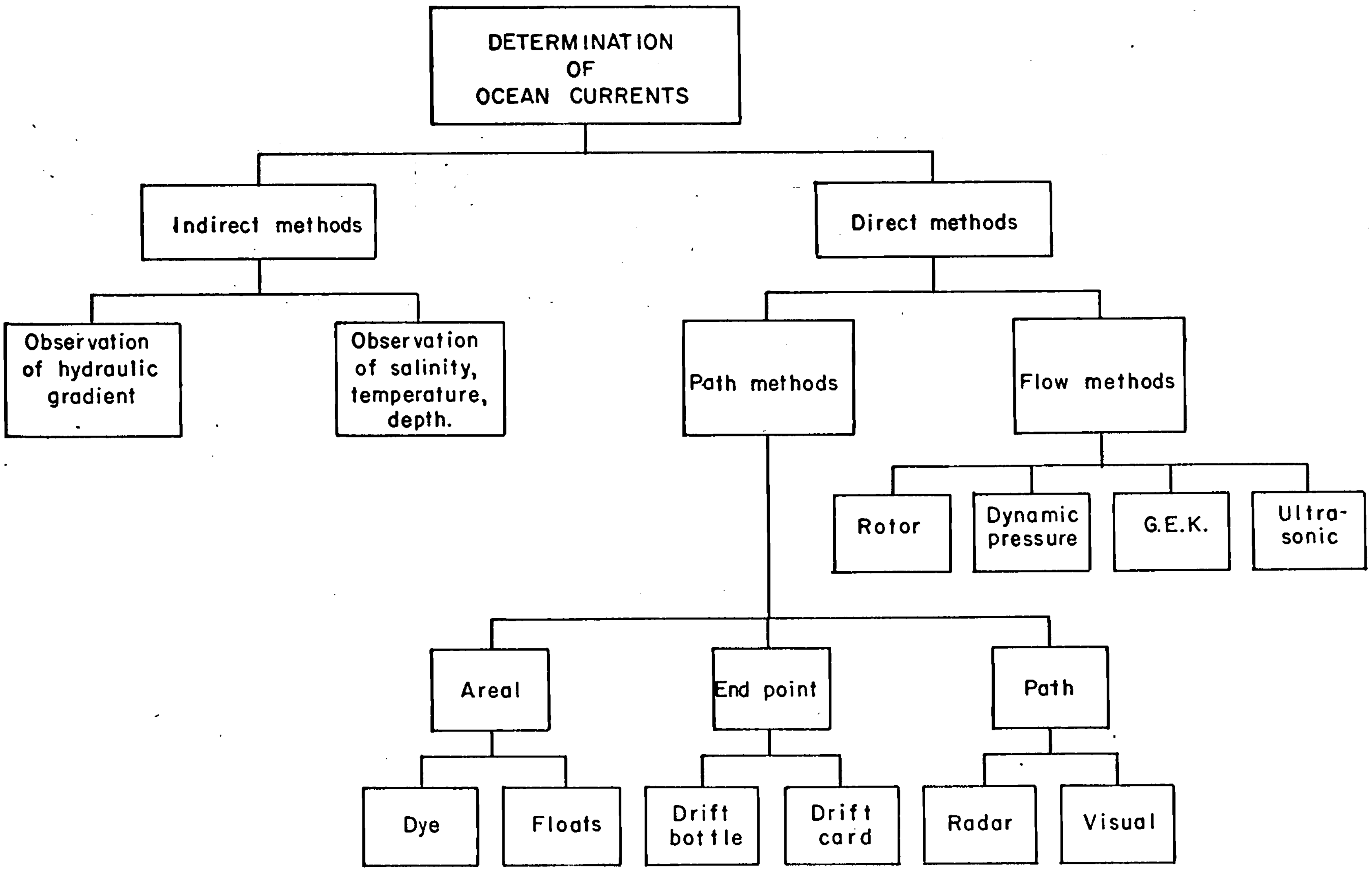


Figure (1). Summary of present methods of determination of ocean currents. (7, p. 44) meters in use today in the propeller category are the Ekman current meter, Roberts radio current meter, and the von Arx meter. The Price current meter, and the Pettersson current meter are of the cup and/or paddle wheel meter type.

The drift type current measuring systems fall into four general classes: 1. surface types, 2. trans-surface types, 3. submerged types, and 4. combined types. The most common surface current measuring system is the surface vessel (ship). Scientific measurements of surface currents can be made by the common drift bottle which is of the trans-surface type. A nearly ideal form of the submerged type is the Swallow float, a free-floating submersible unit that is located and followed by listening to the sound signals the float itself transmits through the water. The combined type employs, for example, a sub-surface drogue attached to a surface float.

The miscellaneous types of current meters cover all types not covered by the rotating element current meters or the drift type current measuring systems. Several examples of the miscellaneous types of current meters include: stationary resistance type, stationary ultrasonic type, and geomagnetic current meters.

The successful measurement of any current system involves not only accurate current measuring devices, but also the accurate knowledge of the position of the current measuring device in space. In the case of the rotating element current meter, one must know where the fixed point of observation lies with respect to the earth - its latitude and longitude. You must, indeed, make certain it is fixed! But in the case of the drift type current measuring system, not only is the investigator interested in the initial point, but also the accurate positioning of the measuring device at successive times. This involves the use of one or several of many electronic positioning systems presently used in navigation over oceanic surfaces. These are of one of two geometrical types: circular methods (radar, shoran, and sonic methods) and hyperbolic methods (Loran, Lorac, Decca and Raydist methods). (7, p. 117)

The basic principle is the same with the electronic methods named or when using astronomic fixes. The drift of a ship making its way under power across an ocean current can be estimated from a comparison of the course made good with the course steered. The discrepancy is an indication of the average speed and direction of the surface current.

II. The data used in the study

Methods of current measurement

A technique similar to the one employed by Volkmann *et al.* (20, p. 573-577) was used in the direct measurement of the surface and subsurface currents off the Oregon coast. This method was chosen because drogues have at least two assets:

1. The use of parachute drogues has proved to be an effective method for gathering information on currents, and
2. The problems in launching and tracing the drogues could be solved with the personnel and equipment at hand.

The parachute drogues (hereafter referred to as drogues) used in this study were of the design as seen in figure (2). The first drogues built are shown in figure (2)A and the modified drogue that was used in the later stages of the investigation and which are presently used are of the design pictured in figure (2)B.

A 28 foot diameter parachute canopy, with a 15 pound weight tied to the spreader bar, was attached to the desired length line and this, in turn, attached to the surface drogue. The surface float consisted of an 18 foot bamboo pole approximately 2½ to 3 inches in diameter at the base tapering to 3/4 to 1 inch at the top. To this pole was attached a 6.00 x 16 inflated automobile inner tube fixed at a point 72 inches from the base of the pole. This was found by experiment to be the point that gave the maximum extension of the pole above the water during the wind speeds that were encountered during the investigation. At the base of the pole was attached a 25 pound weight, doubly secured with 5/32 inch cable and nicopress fasteners. On the upper end of the pole were attached a radar-reflector, a numbered flag, and a 3.2 volt (G.E. #42) light. Power for the light was supplied by a pair of 1½ volt telephone dry cells encased in an ordinary "milk shake" cup filled with parafin. All the cable used in the building of the drogue was either 3/32 inch wire rope (parachute to pole) or 5/32 inch (all weights attached with this thickness) and all cable fasteners were nicopress.

Several modifications were made as the work progressed. The modifications that have proved effective are as follows:

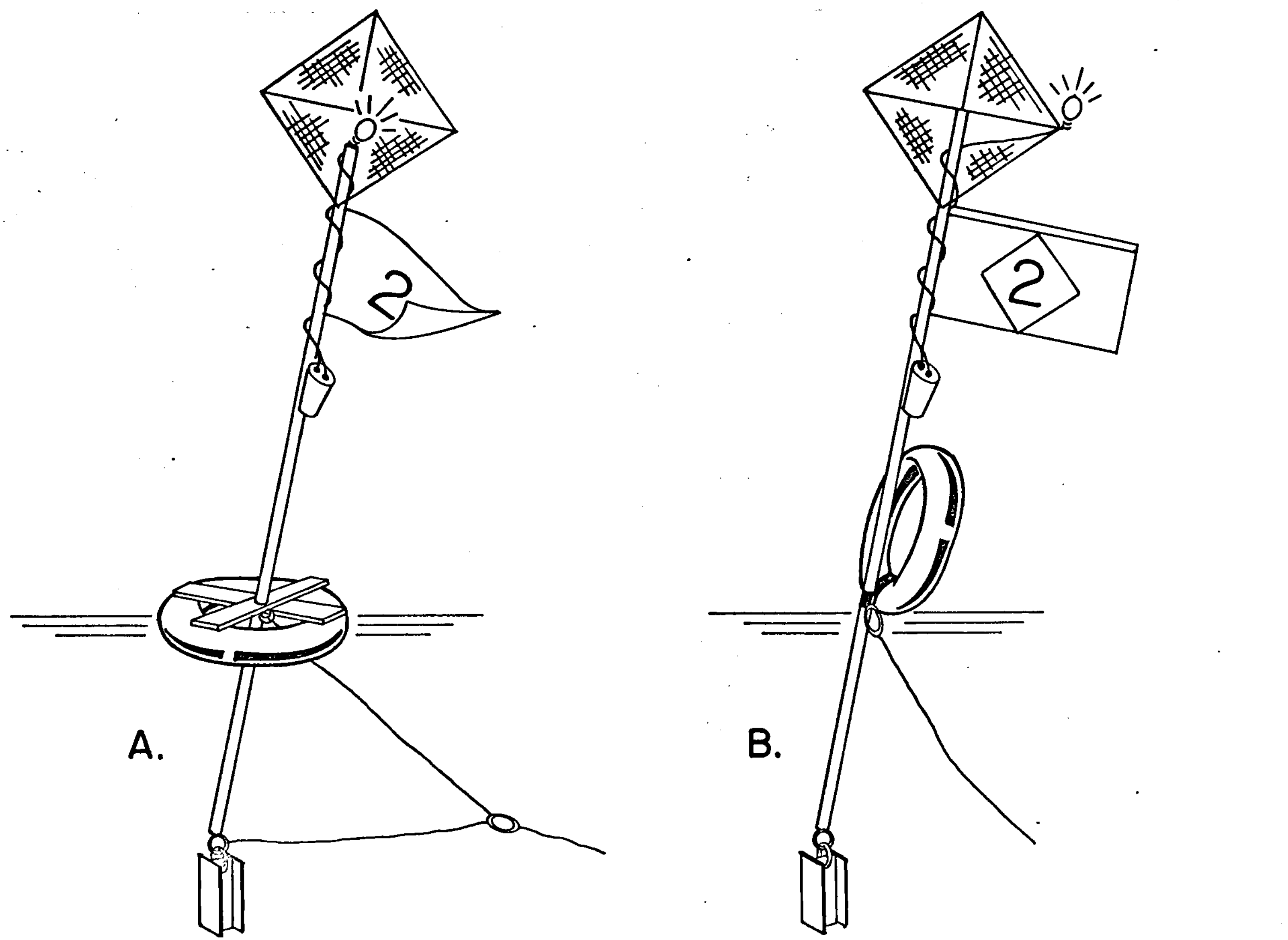


Figure (2). Surface portion of parachute drogue system. A- original drogue, B- modified drogue.

1. Use of the snap that is packed within each parachute for attaching all cables. This was done so that the desired length of cable could be cut in the shop, rolled on a board, and very quickly attached to the drogue and parachute when they are cast free.
2. Use of an ordinary weather balloon, inflated with helium to a diameter of approximately four feet, and attached to fixed reference drogue. This facilitated the visual sighting of the reference drogue, especially when there was considerable swell.
3. Use of various flashing lights in addition to the permanently glowing lights. It was found that a stroboscopic light was more easily sighted in haze or murk than a permanently glowing light.
4. Use of Indian orange, (Cable No. 70072, Standard color card of America) for the color of the drogue flag. This has proved to be the most effective color to see in all types of weather.
5. Use of snap connectors in attaching the cables to the weights and poles. This facilitated the launching of the drogues by enabling the drogue system to be rapidly assembled.
6. Use of a "weak link," a 5 foot piece of nylon cord tied between the surface drogue and the cable attached to the parachute. This facilitated recovery of the surface parts of the drogue assembly by using a "tree pruner" type cutting pole to sever the line.

The basic navigational fixes for initial and final positions of the drogues were made by Loran. However, to track the drogues after their initial placement the shipboard radar (Decca model) was employed. A "reference drogue" was first installed and anchored to the bottom when possible. The range and bearing from the reference drogue to the desired drogue could then be determined from the radar. Readings were attempted every hour on the hour and additional readings were made when desired and possible.

During good weather the radar operator had little difficulty following up to eight drogues at a time, and to a maximum distance of 16,000 yards. However, during marginal or stormy weather it was very difficult to follow any given drogue and still maintain the position of the reference drogue. This required that the ship leave the reference drogue and "hunt" for the desired drogue, and, if found, a Loran fix made of the drogue position replaced the usual radar fix from the reference drogue.

Observations were recorded on prepared sheets as shown in figure (3) in addition to the observation sheet, plottings were regularly made on standard radar plotting boards (H. O. 4665-10, U. S. Navy Hydrographic Office). Hydrographic data were also taken during each drogue cruise; these were recorded on standard hydrographic data reduction forms.

DROGUE RADAR DATA SHEET

Date ________________ Time ________________ PST

Reference Drogue No. ________________ Depth ________________

Position: Loran ________________________________

____

Lat. ________________________________

Long. ________________________________

Drogue No. ________	Range ________	Bearing ________ (Magnetic)
Drogue No. ________	Range ________	Bearing ________
Drogue No. ________	Range ________	Bearing ________
Drogue No. ________	Range ________	Bearing ________
Drogue No. ________	Range ________	Bearing ________
Drogue No. ________	Range ________	Bearing ________
Drogue No. ________	Range ________	Bearing ________
Drogue No. ________	Range ________	Bearing ________

Wind Direction (True) ________________ Speed (MPH) ________________

Remarks (doubtful readings, etc.):

Figure (3). Observation recording sheet used in the later stages of the investigation.

The observations

During the period under investigation, six cruises were made off the Oregon coast in the area shown in figure (4). Each cruise plan called for drogues at depths of 10 meters (considered to be the surface drogue), 50 meters, thermocline depth, 100 meters, 150 meters, 200 meters, and 250 meters. For the earlier cruises, the 1000 meter drogue was used as the reference drogue. For the November cruise an anchored drogue was placed in 1200 fathoms of water for the fixed reference point. A detailed summary of the observations is given in table (2).

Because of the quantity and quality of data taken from the September, 6209 cruise, a special note should be made of the observations. Currents were measured at 10, 50, 100, 150, 200, 250 meters. The 1000 meter drogue was used as the reference point. The maximum time the currents were measured was 65.0 hours, and the maximum distance the drogues were tracked was 23.2 nautical miles. Due to the extremely good weather, the current measurements taken during this cruise include the least observational error to date among these data, thus the September current measurements were used most extensively for comparison and correlation of the currents and hydrographic conditions.

The most difficulty was encountered during the November, 6211 cruise when weather conditions were such that drogues were repeatedly lost after the first few hours, or the Loran was almost ineffective. During this cruise, only one satisfactory hydrographic cast was made.

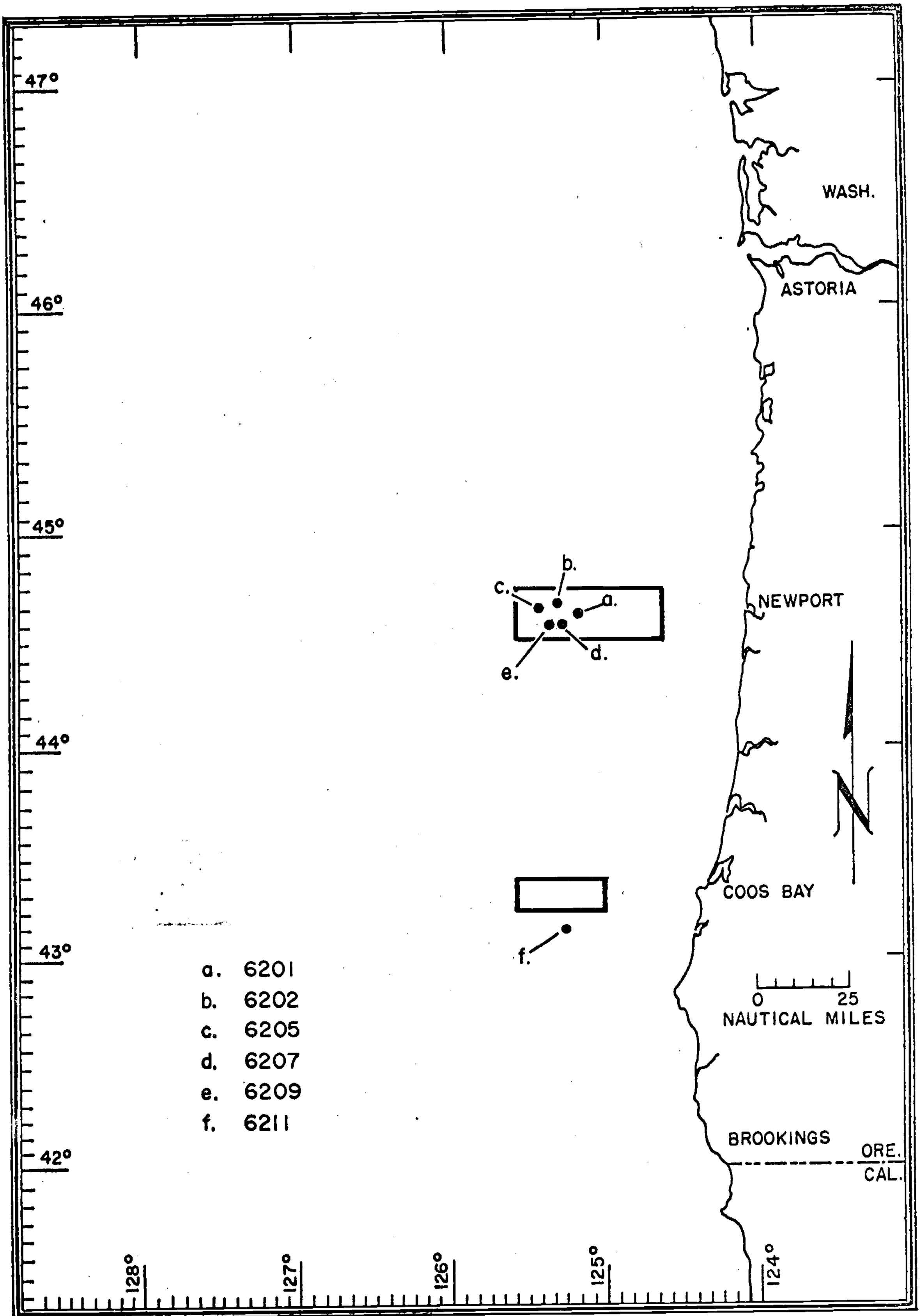


Figure (4). Positions of initial placement of parachute drogues.

Cruise No.	Date	Hydrographic stations		Drogue data			
		no.	depth meters	no.	depth meters	tracking time hr.	No. position fixes
6201	29-31 Jan.	1	576	1	10	53.57	20
		2	205	2	50	53.72	18
		3	200	3	100	53.03	23
		4	200	4	150	53.33	21
				5	200	53.47	24
6202	26-28 Feb.	1	199	1	10	43.33	13
				2	10	43.38	11
		2	200	3	50	42.42	8
				4	100	41.42	13
		3	800	5	150	37.58	12
				6	200	34.60	12
6205	31 May 1 June	1	200	1	10	40.00	12
		2	200	2	10	39.92	12
		3	208	3	50	40.78	12
		4	900	4	100	36.40	11
		5	189	5	150	26.40	9
				6	200	36.63	11
				7	1000	40.53	14
6207	5-7 July	1	800	1	10	35.28	8
		2	200	2	100	42.17	11
		3	200	3	150	42.70	9
		4	200	4	250	43.45	10
				5	550	42.92	9
6209	24-27 Sept.	1	196	1	10	45.42	18
		2	200	2	10	50.23	5
		3	200	3	50	63.73	14
		4	1000	4	100	49.65	24
		5	200	5	150	61.83	33
		6	200	6	200	59.67	33
		7	200	7	250	60.01	33
		8	200	8	1000	64.98	33
6211	17-19 Nov.	1	200	1	10	8.50	4
				2	10	8.50	4
				3	50	16.17	15
				4	100	21.00	16
				5	200	25.75	10
				6	300	20.50	13
				7	1000	27.38	10
				8	anchor	32.83	18

Table (2). Summary of data for six drogue cruises off the Oregon coast.

Data reduction

Data were reduced by two methods. First, the successive radar readings of range and bearing of each drogue relative to a reference drogue or buoy were plotted. The current speed and direction were then determined from the total change in relative positions and the elapsed time. From this was vectorily subtracted the movement of the reference drogue as determined from Loran fixes. This yielded an average velocity for each drogue, that is, for each measured subsurface level. The second method of data reduction was by programming the IBM 1620 computer to handle the data as recorded and to print the velocity components directly between each pair of radar fixes. A flow diagram of the computer program is shown in figure (5).

The input information to the computer consisted of the following information:

A. Initial information

1. Drogue number
2. Time of release
3. Release position
4. Depth of drogue

B. For each observation after the initial observation

1. Drogue number
2. Depth of drogue
3. Time of observation
4. Reference drogue number
5. Reference drogue position
6 Numbered drogue number
7. Numbered drogue position (range and bearing from reference drogue)
8. Wind speed
9. Wind direction

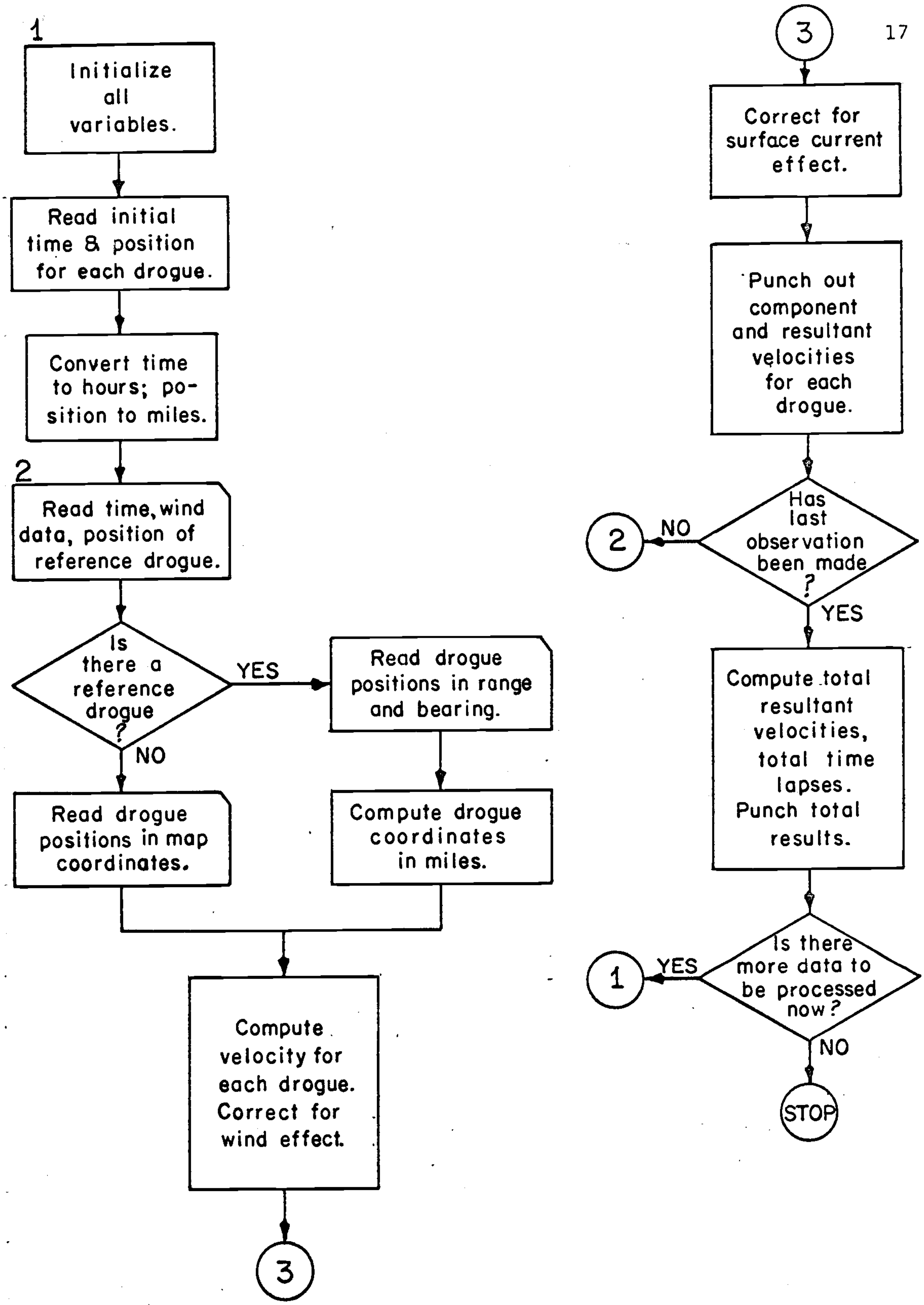


Figure (5). Flow diagram for computer reduction of drogue data.

The output consisted of the following information:

A. For each observation

1. Drogue number
2. Observation number
3. Drogue depth
4. East-West uncorrected velocity
5. North-South uncorrected velocity
6. East-West corrected velocity
7. North-South corrected velocity
8. Time lapse since last observation

B. Summary at end of computer program

1. Drogue number
2. Drogue depth
3. Uncorrected East-West distance
4. Uncorrected North-South distance
5. Uncorrected East-West velocity
6. Uncorrected North-South velocity
7. Corrected East-West distance
8. Corrected North-South distance
9. Corrected East-West velocity
10. Corrected North-South velocity
11. Uncorrected resultant velocity
12. Corrected resultant velocity
13. Total time lapse.

The corrections implied in steps A. 6, A. 7, and B. 7 through 10 were made to the current measurements based on data obtained from D. Brown of Scripps Institution of Oceanography (2). The drag forces applied to the parachute drogue system can be treated as the sum of two components. The first is the drag against the radar reflector, pole, flag, and any other above surface protrusions which are acted on by the surface winds. The second is the drag against the cable, and other sub-surface components, brought on by the currents above the parachute. A graph of the drag forces on the components of the parachute drogue system is shown in figure (6).

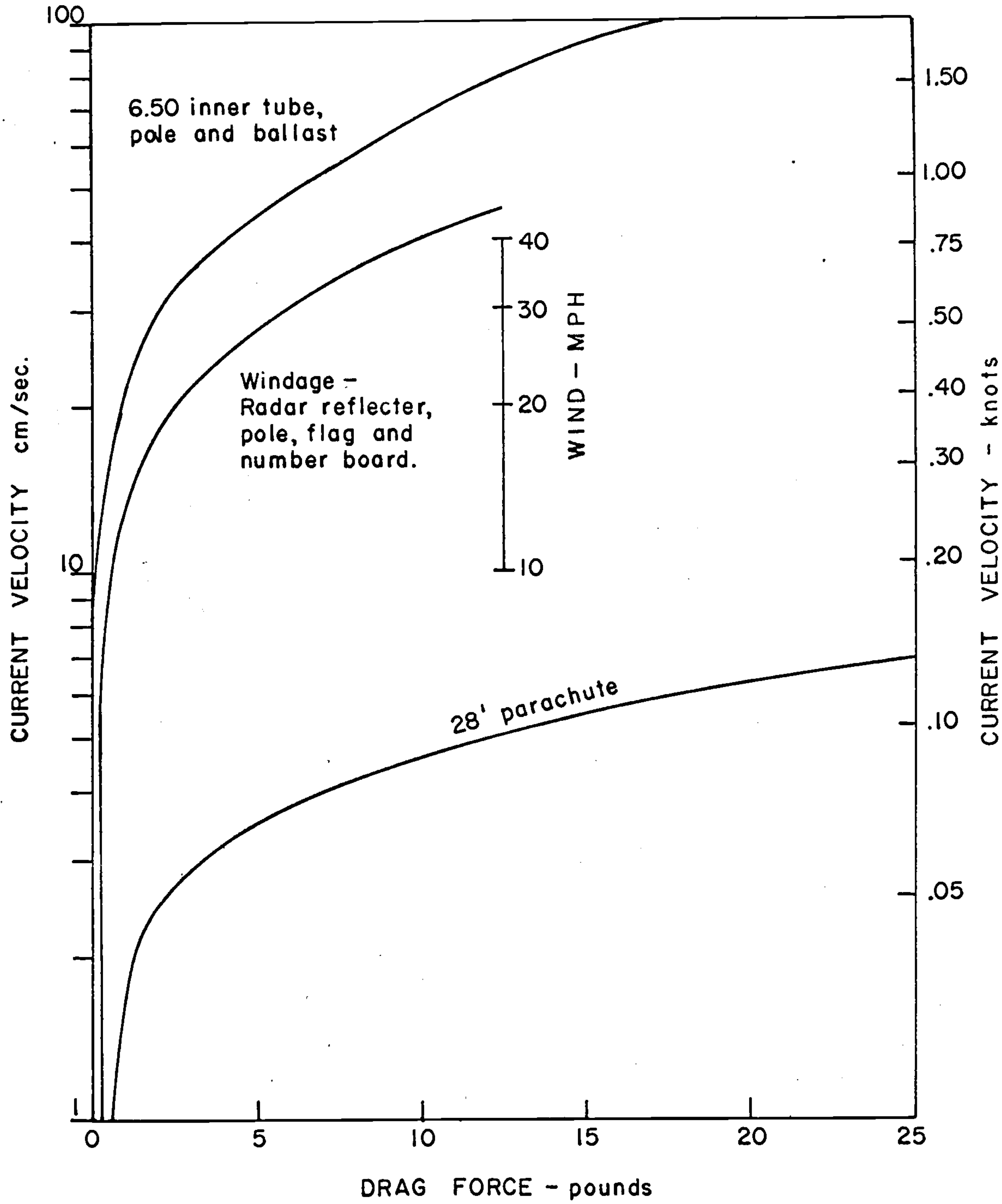


Figure (6). Drag forces on components of parachute drogue system (2).

The average current velocity in reduced form showing the uncorrected and corrected velocities is summarized in table (3) and figure (7).

The information taken from the computer reduction of the drogue data will enable a much closer look at the incremental data than could have been possible without the aid of the computer. Several additional programs will be integrated into the computer analysis as it stands presently. These are the extraction of the tidal components of the motion, and possible analysis of the homogeneity of the system (see section III, General).

The hydrographic data were also processed on the IBM 1620 computer and yielded interpolated values of sigma t and the dynamic height below to the sea surface of each desired pressure surface. For an example of the parameters obtained from reduction of hydrographic data with the IBM 1620 computer, the reader is referred to Hydrographic data from Oregon coastal waters (23).

Estimate of errors

Several errors in current measurement were noted. The primary error occurred in the positioning of the ship. The errors induced in tracking surface drogues with the use of Loran are the same as those encountered when using Loran for measuring the surface current by ship drift.

A sketch of the parallelogram of uncertainty in fixing ship's position appears in figure (8).

Cruise no.	drogue		Average current velocity			
			uncorrected		corrected	
	no.	depth	speed cm/sec	towards °	speed cm/sec	towards °
6201	1	10	10.20	123°35'	10.20	123°35'
	2	50	5.59	133°16'	5.69	132°43'
	3	100	1.63	99°52'	1.69	100°35'
	4	150	1.61	83°13'	1.71	84°18'
	5	200	1.9	4°09'	1.91	7°12'
6202	1	10	16.75	128°36'	16.62	128°14'
	2	10	16.73	128°37'	16.70	128°16'
	3	50	13.26	124°33'	13.14	124°23'
	4	100	12.14	122°52'	12.04	122°19'
	5	150	10.64	125°31'	10.56	124°45'
	6	200	8.69	126°49'	8.62	125°56'
6205	1	10	1.50	126°50'	1.42	123°48'
	2	10	3.07	87°31'	3.77	86°39'
	3	50	1.91	128°00'	2.27	128°35'
	4	100	3.33	77°42'	4.15	80°46'
	5	150	5.29	35°46'	6.11	44°44'
	6	200	3.75	44°34'	4.41	51°27'
	7	1000	6.53	26°39'	7.03	32°36'
6207	1	10	15.27	200°33'	15.48	200°15'
	2	100	7.20	169°26'	7.44	169°53'
	3	150	12.08	183°42'	12.34	183°46'
	4	250	11.18	170°18'	11.41	170°28'
	5	550	4.30	167°15'	4.51	167°19'
6209	1	10	25.77	101°56'	25.79	101°55'
	2	10	22.52	92°21'	22.46	92°12'
	3	50	17.42	86°33'	17.43	86°23'
	4	100	6.66	126°33'	6.81	124°00'
	5	150	1.18	203°58'	1.20	203°58'
	6	200	4.55	283°39'	4.51	283°12'
	7	250	5.12	273°32'	5.00	273°08'
	8	1000	3.47	196°14'	3.47	196°43'
6211	1	10	11.43	320°24'	11.33	321°08'
	2	10	13.72	342°24'	13.62	342°24'
	3	50	6.45	160°03'	6.39	159°35'
	4	100	7.45	148°13'	7.35	145°09'
	5	200	6.96	191°56'	7.02	191°55'
	6	300	8.02	82°50'	8.00	82°06'
	7	1000	4.20	110°55'	4.19	111°32'
	8	anchor	0.0	0°00'	0.0	0°00'

Table (3). Summary of uncorrected and corrected average current velocity.

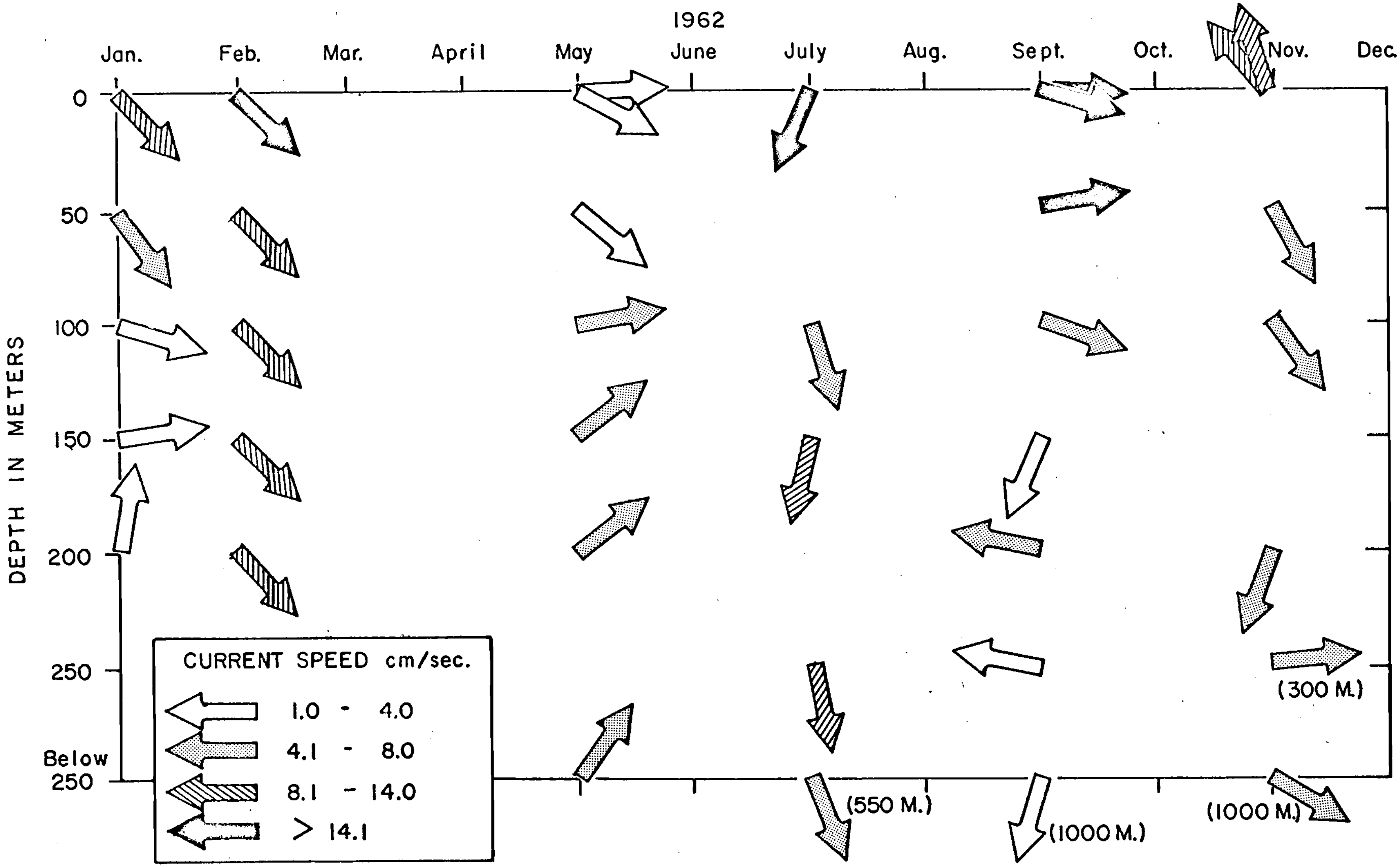


Figure (7). Measured velocities of surface and subsurface currents.

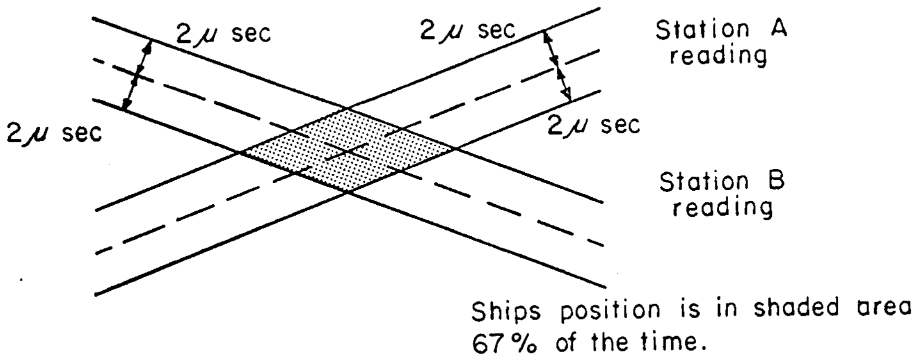


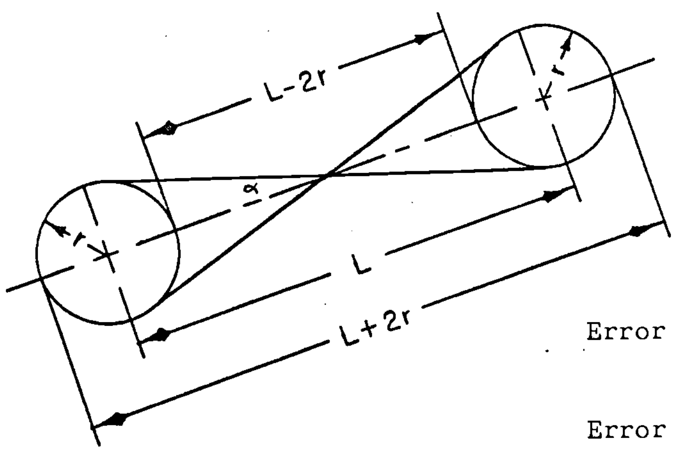
Figure (8). The parallelogram of uncertainty in fixing a ship's position from two sets of time-delay hyperbolas for a Loran type system. (21, p. 229).

von Arx (21, p. 228) states:

> Experience at sea indicates that the standard error in Loran-A fix made in the range 300 to 500 miles from transmitters is approximately 0.7 nautical mile or 1 km...

With the present equipment aboard the R. V. Acona, experience has shown that the average error in positioning with the Loran is $\frac{1}{2}$ mile, (5) which is somewhat better than stated by von Arx.

The average error in direction and distance of travel of the drogue can be appreciated from the geometry shown in figure (9).



Error in direction: $\alpha = \text{arc tan } \frac{2r}{L}$

Error in speed = $\frac{2r}{\text{time}}$

Figure (9). Average error in travel of drogue by Loran measurements.

In figure (9), r is the radius on the equivalent circle of standard error around each Loran fix, L is the distance between the ship and the surface drogue, and α is the maximum angle between true and computed directions of travel. For example, if the 50 meter drogue for the September, 6209 cruise was tracked 21.6 n. miles in 63.7 hours, assuming the radius of the equivalent circle of standard error was $\frac{1}{2}$ n. mile, then the maximum error in direction would be 3 degrees and the maximum error in speed would be 0.9 cm/sec.

A second error in the measurements of currents with the use of the drogues occurs because there is wind drag on the surface portion of the drogue system, and also current drag on the portions of the underwater components, including cable, that are above the parachute. These errors can be appreciable, especially if the velocities of the respective wind and currents are large. Therefore, a correction was applied to each increment of distance between every observation. The method whereby this correction is made is discussed in section II, Data reduction.

III. Results

Surface currents

For the surface waters of the oceans, there is much information available in addition to the drogue results.

Beginning with June 1959 and continuing to date, for each hydrographic cruise made by the Department of Oceanography, Oregon State University, drift bottles have been cast free at pre-determined stations. Reported findings of the drift bottles yield no direct current measurements (other than the minimum velocity assuming straight line travel), but they are of considerable value in describing general trends of surface water transport. The number of drift bottles returned and their recovery points have been summarized from June 1960 through May 1961 (23, p. 26-27). Data taken since May 1961 were incorporated with the previous published data into a gross summary of general drift bottle movements. Since there has been no continuous placement of drift bottles by month in the same position as the initial placement of the parachute drogues, a composite of drift bottle movements was made from drift bottles released in the area outlined with a solid line in figure (4). The composite, by month, is shown in figure (10) by a broad arrow originating from 44.5° North, 125° West.

Surface currents have been observed for many years from the observations of ship's drift. The Atlas of surface currents Northeastern Pacific Ocean (18, p. 1-12) shows monthly prevailing and resultant surface currents in the area under investigation. The Hydrographic Office presents the information in one degree of latitude and longitude squares showing a resultant average current speed and direction based on a recorded number of ship drift observations. The point of initial placement of the parachute drogues was approximately 44.5° North, 125° West, so this point was selected as the reference point on each monthly chart, and the current velocity was averaged about this point. Table (4) shows the monthly average resultant

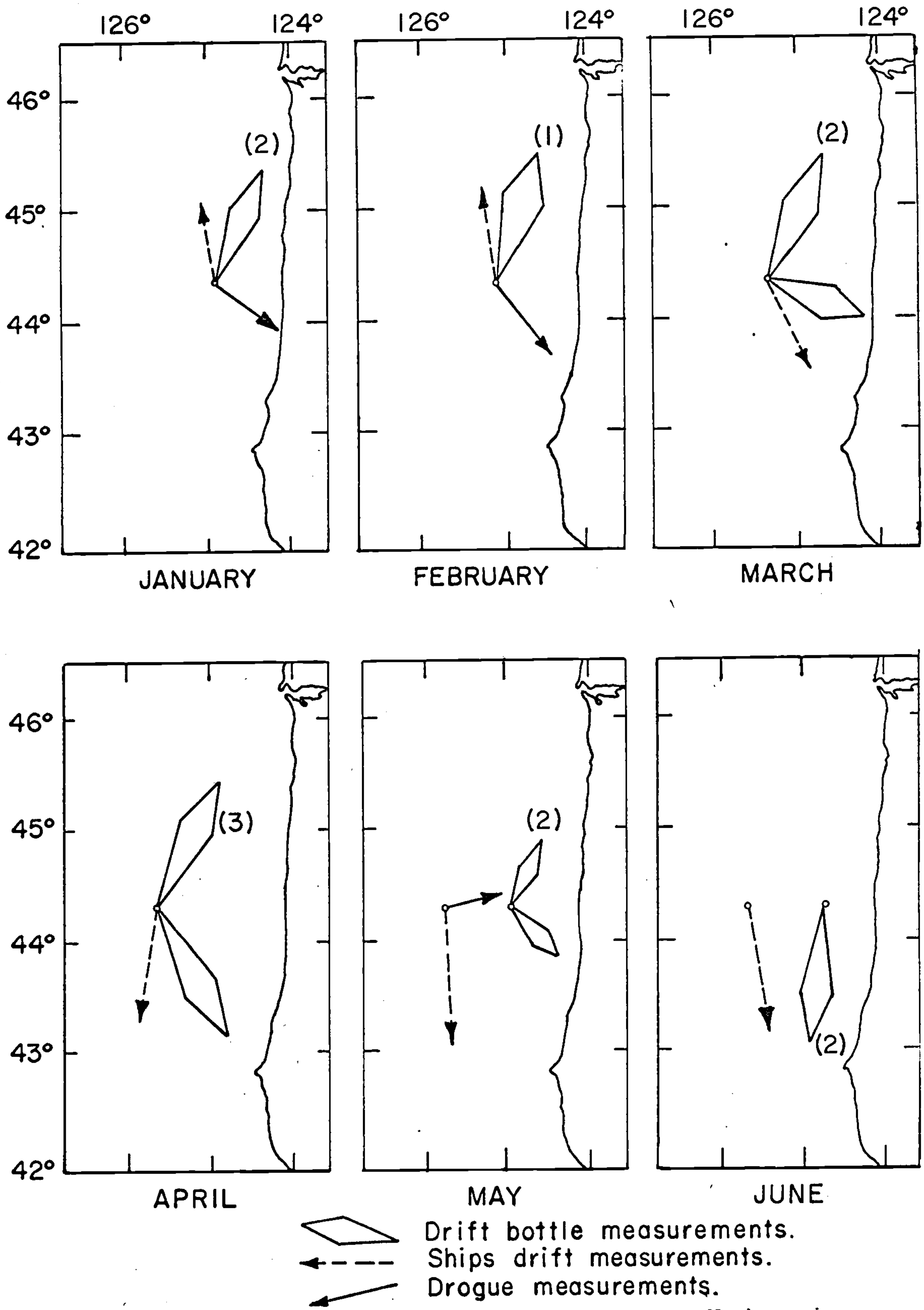
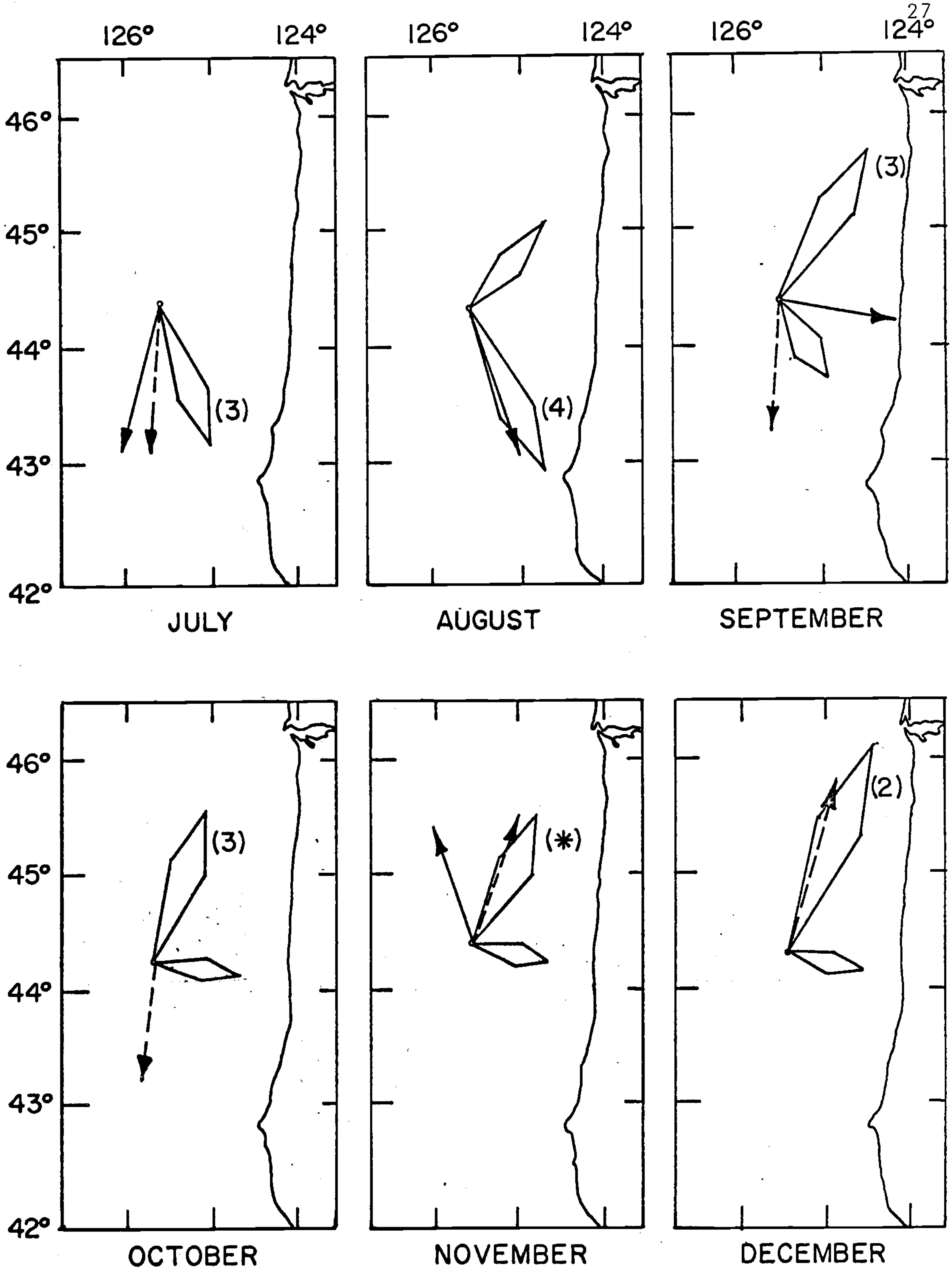


Figure (10). Surface currents off the Oregon coast. Numbers in parenthesis refer to years of drift bottle data available.



Surface currents off the Oregon coast,(con't). (*) - No drift bottle data available, interpolation between October and December data.

current obtained by this method. Also shown are the total number of current observations used in the computation.

Month	Average Current Velocity Speed cm/sec	Towards	No. Observations
January	8.1	343°	150
February	8.8	352°	130
March	8.6	171°	148
April	10.5	185°	146
May	18.8	181°	157
June	15.4	179°	150
July	16.7	187°	150
August	13.5	175°	154
September	13.5	192°	151
October	6.8	204°	132
November	10.4	009°	138
December	8.1	003°	92

Table (4). Average current velocity taken from observations of ship drift. (18, p. 1-12)

The resultant average current velocity based on ship drift is drawn on the composite of drift bottle data (figure (10)), indicated as a broken line arrow. Because the drift bottle data show no absolute speeds, no attempt has been made to indicate speed of the ship drift current, and only the direction of the resultant current is shown.

Surface current velocities from drogue measurements are shown in table (3). The current measurements displayed in table (3) point out several significant results. The maximum average velocity (corrected or uncorrected) measured during any month was 25.8 cm/sec., while the minimum velocity was 1.4 cm/sec. All currents, with one exception, stronger than 5 cm/sec had a southerly component. The exception noted was during the month of November.

When the current velocity taken from drogue measurements was drawn on the composite of the drift bottle data (figure (10)), the direction of the surface current is shown by a solid arrow. In the cases where two surface drogue measurements were made during any one cruise, an average of the two was computed, and the average appears as the solid arrow in figure (10).

Discussion

A great variability appears in the speed of the average surface currents for any given month. For example, from observations of ship drift (hereafter called ship drift) during May, the average speed of the surface currents is shown to be about 19 cm/sec., whereas, from direct measurements with drogues, the average current proved to be about 2 cm/sec. Thus, the absolute speed of any given surface current measurement depends not only on the month of observation, but also is highly dependent on other factors, probably the particular weather system that is present during the period of observation. It is thus more meaningful to discuss surface current speed in general terms rather than specific numbers.

With this in mind, let us group the specific current speeds in the following way:

Absolute Speed cm/sec	General Term
1-12	slow
13-24	moderate
25 and greater	fast

Using the above grouping, the correlation between the drogue and ship drift results is more apparent.

Surface Current Speed

Month	Drogue measurements		Ship drift
	uncorrected	corrected	
Jan	slow	slow	slow
Feb	moderate	moderate	slow
Mar			slow
Apr			slow
May	slow	slow	moderate
Jun			moderate
Jul	moderate	moderate	moderate
Aug			moderate
Sept	fast	fast	moderate
Oct			slow
Nov	slow	slow	slow
Dec			slow

Table (5). Representation of absolute surface current speeds in general terms.

The direction of flow can also be compared. But with three exceptions, the ship drift, the drift bottle records, and the drogue information all show a similar directional pattern. The three exceptions are noted and will be discussed in the following monthly analysis of the mass movement of the surface system.

January. Drift bottle records have shown that the general movement of the surface waters is towards the north with a strong on-shore component. Two years of drift bottle data during the month of January were available. Ship drift has shown the general movement again to be northern, but with a slight off-shore tendency. The drogue measurements taken during January 1962 indicated the surface current was southerly and strongly on-shore. The southerly movement of the drogue can be attributed, perhaps, to a relatively long period of west through northwest winds before and during the measurements.

February. Drift bottle records indicate the general movement to be northerly, with a moderate on-shore component. Only a single year of drift bottle data was available during the month of February. Ship drift indicate the direction also to be almost due north. The drogue measurements taken during the month of February 1962 show, as in January of the same year, a southerly tendency but again with a strong on-shore component. A similar duration of west through northwest winds were noted before and encountered during, the February cruise. Thus the southerly currents can be attributed to this phenomenon as in January.

March through November with the exception of October. For these months, drift bottle records, ship drift and drogue information, when available, all show similar directions for the surface currents. Beginning with March the tendency is to have a weak southerly, and moderate to strong on-shore surface current. The tendency as the months pass is that the current becomes stronger in the southerly direction and weaker in the on-shore component, becoming a weak to moderate off-shore surface current culminating in the month of July. After July, there is a slow weakening of the southerly component, a strengthening of the on-shore component, and then, about November, the transition is complete to a strong northerly current with a strong on-shore component.

October. No drogue information is available during this month so the discussion must be centered around the variation of the direction between the drift bottle records and the ship drift. Three years of drift bottle data have shown that almost without exception all drift bottles cast free about 50 miles from shore have moved rapidly north to north-northeast. The data from the ship drift shown that the current is very weak and possibly omni-directional, but if a specific direction is to be placed on the resultant of the observations, the direction would be south.

With the information available, and with the exceptions, it is then possible to summarize the general speed and direction of the surface currents off the Oregon coast. When the current is obviously undergoing a transition, this is indicated in this summary. A transition can be described as a change in current movement from strong on/off-shore to weak on/off-shore and from strong north/south to weak north/south. A summary of the surface currents off the Oregon coast appears in table (6).

Month	Speed	Direction	Comments
Jan	Slow	Northerly; Strong on-shore component	
Feb	Moderate	Northerly; Moderate on-shore component	
Mar	Moderate	Northerly-Southerly; Weak on-shore component	Transition
Apr	Moderate	Southerly; Weak on-shore component	
May	Moderate	Southerly; Weak on-shore component	
Jun	Moderate	Southerly; Weak on/off-shore component	Transition
Jul	Moderate	Southerly; Moderate off-shore component	
Aug	Moderate	Southerly; Weak on/off-shore component	Transition
Sep	Moderate	Southerly; Weak on-shore component	
Oct	Slow	Southerly-Northerly; Moderate on-shore component	Transition
Nov	Moderate	Northerly; Strong on-shore component	
Dec	Slow	Northerly; Strong on-shore component	

Table (6). Summary of surface current velocities.

Sverdrup et al. (15, p. 725) has indicated that during the months of November, December, and January, the Davidson current runs north along the coast to at least latitude 48° North, which encompasses all of the area under investigation. Sverdrup does not define longitudinal limits, but designated the near-shore distance as "along the coast."

However, as can be seen from the summary of surface currents (table (3)) and also by diagram in figure (10), the movement of the surface water appears to have a very defined on-shore movement during this period. It appears that the major component of the surface current is on-shore and only a small portion of the total surface flow is in the northerly direction.

Doe (4, p. 21), in the study of the surface currents off the Canadian Pacific coast, has shown that during three months (August, May, and March) the current speed is small. Average values are of the order of 5 cm/sec. or less and maxima up to 20 cm/sec. in spring. These measurements agree with the current measurements taken off the Oregon coast during the same seasons.

Subsurface currents

A summary of the average currents at each subsurface level measured with the parachute drogue appears in table (3). In addition, a diagram of the surface and subsurface currents appears in figure 7.

The examination of the subsurface data will be described in several steps. Initially, the currents will be examined to see if they "fit" one of the most widespread types of oceanic flow, geostrophic motion. The geostrophic approximation will be discussed, and the "fit" will be presented following the discussion of the geostrophic approximation. After this step, the currents that show signs of other than geostrophic motion will be examined.

The geostrophic approximation

For several decades oceanographers have been making use of the geostrophic relation to estimate flow in the ocean. Wust's (cited by 16, p. 674) comparison of the currents in the Florida Straits with direct measurements stands as an early example of the accuracy that can be obtained, at least in some cases, if adequate data are available. Knauss (8, p. 380 and 9, p. 265-286) has also compared currents directly measured with those implied from geostrophic calculations.

In order to test the usefulness of this approximation off the Oregon coast, a comparison of the measured currents with those derived from the geostrophic equation will be made. The geostrophic method provides a means for computing the field of motion in a fluid from a knowledge of the internal distribution of pressure.

From the slope of the isobar and from a knowledge of the latitude of observations, it is possible to calculate the horizontal components of geostrophic motion at a depth (z) from the finite-difference form of the geostrophic equation

$$V_x = \frac{1}{\rho f} \left(\frac{\Delta P}{\Delta x}\right)_z \qquad (1)$$

where V_x refers to the horizontal components of geostrophic motion in the x direction, ρ is the average density of the mass of water between surfaces, f is the Coriolis parameter, and $\left(\frac{\Delta P}{\Delta x}\right)_z$ is the slope of the isobaric surface at depth z.

Normally, direct information on the pressure field is also lacking. Therefore, the density of ocean water is observed as a function of depth and it is then possible to compute the change in pressure as a function of depth from the hydrostatic equation. Let it first be assumed that the density is independent of the coordinates. In this case, the distance between any two isobaric surfaces is expressed by the equation

$$\Delta h = \frac{\alpha}{g} \Delta p \tag{2}$$

where Δh is the distance between two isobaric surfaces, α is the specific volume, g is the acceleration of gravity, and Δp is the pressure difference between the two isobaric surfaces. This equation simply states that the geometrical distance between isobaric surfaces is constant for constant specific volume, and it defines completely the internal field of pressure (15, p. 407).

Normally the density in the ocean increases with depth and a relationship between pressure and depth by numerical integration of a number of terms of the form given in equation (2) must be performed.

If at two localities in the ocean the average specific volumes are different, then the thickness of the layers between isobars is found to be different, and it is evident that between the two points of observation, the top and bottom isobaric surfaces are inclined to one another. One or both must slope relative to the horizontal. If one of the isobaric layers can be assumed to be exactly horizontal, it is possible to calculate the slope of the other.

If the geostrophic equation (1) is combined with the hydrostatic equation (2), an expression for the geostrophic velocity on a given pressure surface p is obtained

$$V_x = \frac{g}{f} \left(\frac{\Delta h}{\Delta x} \right)_z \tag{3}$$

where the terms are defined above.

For the simplicity of computation, the expression is written in terms of the depths below the surface at which a given isobaric surface (p) is observed to lie at two places, say A and B and distance L apart:

$$C_g = \frac{g}{f}\left(\frac{\Delta h_A - \Delta h_B}{L}\right) \tag{4}$$

where Cg refers to the component of the velocity that flows at right angles to the line joining the two points A and B (21, p. 246).

The average slope $\left(\frac{\Delta h_A - \Delta h_B}{L}\right)$ between the two points can be computed from the hydrographic data collected at the points. For a complete description of the flow, at least three points of observation are required.

Discussion

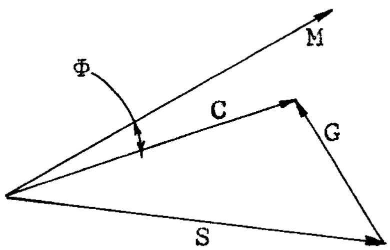
Correlation between subsurface currents and the geostrophic approximation

As discussed in the section on the geostrophic approximation in order to completely describe both the north-south and the east-west components of geostrophic motion, three properly spaced sets of hydrographic data must be obtained. The data that were used in the computation of the geostrophic currents were reduced from the information obtained from standard hydrographic stations taken during the several cruises (see table (2)). Dynamic height relationships were computed from interpolated values of temperature and salinity processed with the IBM 1620 computer to yield standard levels of dynamic height referred to the surface of the ocean (see section II, Data reduction).

During one cruise only (September, 6209) were three suitable hydrographic stations made. During the other cruises, the hydrographic stations were so grouped that only a small distance existed between the several stations, or the stations were taken on a line, yielding only the north-south or the east-west slope of the isobars.

By computing the dynamic height differences between three points on an isobaric surface, the slope of the isobaric surface relative to the sea surface can be computed. Then, by the use of the geostrophic equation, the relative current on the isobaric surface may be computed. If the surface velocity is known, the relative current can be converted into an absolute current velocity by the vector addition of the surface and relative currents.

If the relative current is truly geostrophic, then the current obtained from the vector addition of the surface current to the geostrophic current must be identical to the actual current at the depth of the isobaric surface. This procedure is illustrated in the accompanying diagram.



S = surface velocity
G = geostrophic velocity
C = calculated velocity
M = measured velocity
Φ = directional difference, measured to calculated

Figure (11). Vector diagram of measured and calculated currents.

The geostrophic currents were computed using the method outlined in section III, The geostrophic approximation. A summary of the geostrophic currents for the September, 6209 cruise appears in table (7).

Table (7). Geostrophic currents relative to the surface for the September, 6209 cruise

Depth - meters	Geostrophic currents relative to the surface	
	speed cm/sec	toward degrees
0	0	0°
50	8.4	117°
100	15.6	119°
150	19.5	117°
200	20.7	115°

Table (8) summarizes the calculated and measured subsurface currents for each month except November when the lack of two suitable hydrographic stations prevented a comparison from being made.

During the January, February, May, and July cruises, the resultant average north-south or east-west component of speed is shown. The component depends on the positions of the hydrographic stations (i.e. a north-south hydrographic section results in east-west component of geostrophic flow; east-west hydrographic section results in a north-south component of geostrophic flow). The measured speed is the component of the measured velocity perpendicular to the hydrographic line. The third row in each case shows the arithmetic difference between calculated and measured speeds, neglecting sign. The September

Month				Depth - meters 50	100	150	200
Jan	Resultant ave E-W* component of speed	Calculated speed cm/sec		7.6	-8.8	-8.9	-10.8
		Measured speed cm/sec		4.1	1.5	1.6	0.2
	Difference, calculated less measured speed cm/sec			3.5	7.3	7.3	11.0
Feb	Resultant ave N-S* component of speed	Calculated speed cm/sec		-8.7	-7.1	-4.3	-
		Measured speed cm/sec		-5.2	-6.4	-5.3	-
	Difference, calculated less measured speed cm/sec			3.3	0.7	1.0	-
May	Resultant ave N-S* component of speed	Calculated speed cm/sec		0.6	7.4	10.3	-
		Measured speed cm/sec		-1.6	0.6	4.3	-
	Difference, calculated less measured speed cm/sec			2.2	6.8	6.0	-
July	Resultant ave E-W* component of speed	Calculated speed cm/sec		-	5.7	11.8	-
		Measured speed cm/sec		-	1.4	-0.9	-
	Difference, calculated less measured speed cm/sec			-	4.3	12.7	-
Sept	Resultant average velocity	Calculated	Speed cm/sec	18.0	10.9	8.6	7.5
			Direction °	92.8	79.3	67.1	62.9
		Measured	Speed cm/sec	17.2	8.9	1.2	4.5
			Direction °	85.3	106.9	202.1	283.0
	Difference, calculated less measured velocity		Speed cm/sec	0.8	2.0	7.4	3.0
			Direction °	7.5	27.6	135.0	220.1
	Error in speed and direction based on Loran error of $\frac{1}{2}$ n. mile		Speed cm/sec (2r/time page 23)	0.9	1.1	0.9	0.9
			Direction ° (α page 23)	3	9	49	12

Table (8). Summary of calculated and measured currents.
* North and East directions are noted by positive speeds
South and West directions are noted by negative speeds

cruise shows not only the total average speed, but direction as well.

Several important features of subsurface flow can be discerned after a close examination of the results tabulated in table (8).

From the differences in speed for the five tabulated months it appears inconclusive that any depth interval is more or less geostrophic than that above or below it. In other words, upon examination of speed only, there is not any definitive depth where the geostrophic flow becomes non-geostrophic. However, the significant part of table (8) appears to be the differences in direction between the calculated and measured velocity for the September, 6209 cruise. The relatively small angle (7.5°) at the 50 meter depth, with the slightly larger angle (27.6°) at 100 meters shows only a slight variation between the measured and calculated values of the subsurface flow. At 150 meters, however, the difference in direction (135.0°) is significantly larger than at the 100 meter depth. This seems to warrant the examination of the possibility of some non-geostrophic force acting on the system. A similar large difference in direction is found at 200 meters.

More meaningful results may be shown if the data are first examined for the effects of the inherent errors involved in measurements of this type.

An error that has not been quantitatively determined is the human error. This includes such things as non-familiarity with the radar set, etc. It is quite obvious that errors of this type are present, but to what extent remains essentially unknown.

A portion of the error in measurements can be attributed to Loran navigational error and these we can compute approximately. These errors have been noted in table (8) and the method that was used in the determination of the errors is discussed in section II, Estimate of errors. For the five cruises under consideration, the maximum Loran error in position was 44° (May cruise at 10 meters) and the maximum Loran error in speed was 0.9 cm/sec (May cruise at 150 meters).

For September, if it is assumed that the Loran error is a maximum at each depth, then the differences that cannot be accounted for in the Loran error between the calculated and measured velocities are: 50 meters, speed 0 cm/sec, and direction 4.5°; 100 meters, 0.9 cm/sec and 18.6°; 150 meters, 6.5 cm/sec and 86.0°; 200 meters, 2.1 cm/sec and 208.1°

It appears reasonable that human error could fully account for the remaining difference in measured to calculated velocity at 50 meters and possibly account for the same remaining error at 100 meters, but the obvious break between geostrophic and non-geostrophic current comes below the 100 meter level and appears convincingly in the 150 and 200 meter observations.

The implication of this shift from geostrophic to non-geostrophic currents will be discussed in the next part. The 100 meter level seems to be more of a convenient number than a realistic cut-off point for geostrophic flow; it might be more meaningful to summarize the current discussion thus far by indicating that the currents appear to be geostrophic to about 100 meters, but below this level a rapid change from geostrophic to non-geostrophic flow takes place, and by 150 meters the nature of the flow no longer fits the geostrophic approximation.

Non-geostrophic currents

Upon examination of figure (7), one significant fact is evident almost without exception in the vertical profile of subsurface currents: the speed is most rapid at the surface, diminishing to the smallest velocity occurring between 50 and 150 meters, and then increasing again below 150 meters. The one exception occurred in May (cruise 6205) when speeds increased almost continuously to the deepest drogue level, 1000 meters.

These facts are suggestive of a "driving" current at some depth below our drogues. The examination of the deeper currents for indications of an acceleration system seemed worthwhile.

For a current system to be in equilibrium, all forces acting on each particle of water must be in balance. Neglecting for the moment all vertical forces, the forces acting on a particle in motion are:

1. Pressure gradient force
2. Coriolis force
3. Frictional force

If the system is not accelerating, then the forces must balance. If the system is accelerating, then the resultant of the forces must be proportional to the acceleration of the particle.

If the magnitude and direction of the particle velocity are known, then the Coriolis force is known both in magnitude and direction. Using hydrographic data, the pressure gradient force can be determined both in magnitude and direction. Thus, there remains only the frictional force to be either estimated or measured.

The most promising method to describe the frictional component would be to consider the transport of momentum across surfaces normal to the velocity gradient. If horizontal turbulence is neglected, the consideration of transport of momentum leads to the frictional terms (15, p. 475):

$$R_x = \frac{\partial}{\partial z}\left(A \frac{dV_x}{dz}\right) ; \quad R_y = \frac{\partial}{\partial z}\left(A \frac{dV_y}{dz}\right). \qquad (5)$$

Because it appears that non-geostrophic forces (in this case friction) are acting below 100 meters, an attempt to determine quantitatively the frictional component of motion at this level was undertaken. If it is determined that the friction balances the resultant of the pressure gradient and Coriolis forces, then it can be stated that the currents below about 100 meters are in equilibrium. If not, then the flow must be accelerating.

North-south and east-west velocity versus depth was plotted at 150 meters and the change in slope of this curve was determined by integration over the depth from 100 to 200 meters. Next, from representative values of the eddy viscosity (A) taken from The Oceans (15, p. 494), A was assumed to be 500 gm/cm/sec. From these, R_x and R_y were determined. These terms turned out to be small, of the order of 0.3×10^{-4} cm/sec^2.

When these R components were added to the respective north-south and east-west components of pressure gradient force and Coriolis force, (calculated earlier in the determination of the geostrophic approximation), it was discovered that there resulted a net force (force per unit mass in all cases) of 10.8×10^{-4} cm/sec^2 in the east direction and a net force of 17.9×10^{-4} cm/sec^2 in the north direction. If A was assumed to be 1000 gm/cm/sec, (doubling the previous A), the net force is changed by only 5 percent. Thus, from considerations of frictional terms neglecting horizontal turbulence, it appears that the system below about 100 meters is not in equilibrium, i.e. it must be accelerating.

The turbulent nature of the waters off the Oregon coast is little understood. It seems reasonable to assume there are horizontal eddies causing horizontal turbulence, a non-geostrophic term. Thus the assumption that there exists a known eddy diffusivity, may be invalid. The entire problem of the determination of a frictional component is based on such limited data that any statement about the acceleration of the current system below about 100 meters would be inconclusive - the question is not resolved in a single case.

General

Several factors may play an important part in the accurate determination of the current structure off the Oregon coast. These are discussed below.

Effect of bottom topography

Bennett (1, p. 631) suggested that in his study of the Northeast Pacific Ocean bottom topography affected only two cases of currents above 2000 meters. Both cases involved an area in which seamount chains were present and in all other areas the currents above 2000 meters were assumed unaffected by bottom topography. The average depth of water during the drogue cruises was approximately 1500 fathoms. Since this is very much deeper than the deepest drogue, we have assumed the effect of the bottom topography can essentially be neglected.

Homogeneity

It was assumed in all the current measurements that the drogues measured only those currents within a homogeneous system. For the longer current measurements, it is quite possible that the drogues passed into a region of mixing or that the circulation experienced changes in time, and the measurements taken at the end of the period were not of the same system that those taken at the beginning of the measurement period.

Tidal currents

The cruises were designed to cover one or more complete tidal cycles whenever possible (25 hours, 50 hours, etc.). This interval by itself would tend to eliminate tidal effects from the average velocities measured.

The individual velocity estimates determined between each pair of fixes throughout the cruise have been examined for indications of tidal flow. North-south and east-west components of surface currents were plotted versus time; the period of the tidal oscillation and any sub-periods were super-imposed on the same diagram and examined for any correlation. For the measurements made, there appeared to be no obvious correlation.

IV. Summary

The current system off the coast of Oregon is a small part of the California current system, which flows all year from north to south. Seasonal effects produce local changes in the current pattern. This pattern can be described in the surface layers through four transition periods which occur in the months of March, June, August, and October.

The currents below the surface and to a depth of approximately 100 meters are shown to be geostrophic in nature. Thus the current pattern can be completely described with the use of hydrographic data and a knowledge of the surface currents.

The currents below 100 meters and to a depth of 250 meters are highly variably and non-geostrophic. Additional measurements of current flow and analyses of results are needed to explain these facts.

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