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COASTAL CURRENTS ALONG THE PACIFIC COAST OF THE UNITED STATES

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PREFACE

Sailing along in clear weather, the navigator can determine the position of his vessel by bearings on landmarks or other terrestrial objects; but in thick weather he can no longer do this, and it then becomes a matter of prime importance that he know the velocity and direction of the currents to which his vessel may be subject. It was therefore primarily for the purpose of obtaining information for the use of the mariner that the investigation of the currents along the coast was undertaken.

Attention was first directed to the Pacific coast of the United States, because there the currents constitute an important factor in coastwise navigation, since along the more than thousand miles of shore line from the Mexican border to the Strait of Juan de Fuca harbors are many miles apart, sailing courses long, and periods of thick weather of comparatively frequent occurrence. This publication embodies the results of the investigation.

In connection with this publication, attention is directed to three other Coast and Geodetic Survey publications containing current and tidal data for the Pacific coast of the United States. These are Current Tables, Pacific Coast, North America; Tide Tables, Pacific Coast, North America; and Tides and Currents in San Francisco Bay.

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COASTAL CURRENTS ALONG THE PACIFIC COAST OF THE UNITED STATES

By H. A. Marmer, *Assistant Chief, Division of Tides and Currents, Coast and Geodetic Survey*

I. INTRODUCTORY

The current observations discussed here were made from the five light vessels stationed along the Pacific coast of the United States. The location of each of the light vessels is shown on the accompanying sketch map. The most southerly one is stationed off the entrance to San Francisco Bay and the most northerly one at the entrance to the Strait of Juan de Fuca. Between these—a distance of about 670 nautical miles—the other three light vessels are irregularly spaced. From San Francisco Light Vessel to Blunts Reef Light Vessel the distance is about 180 miles, and from the latter to Columbia River Light Vessel about 350 miles. Umatilla Reef Light Vessel is stationed 120 miles above Columbia River Light Vessel and 20 miles below Swiftsure Bank Light Vessel.

With the cooperation of the Lighthouse Service, under whose jurisdiction the light vessels come, it was arranged to have current observations made at the beginning of each hour of the day. The arrangement provided for the observations to be made by the officers and crew of the light vessels. The regular routine work on the light vessels permitted only such observations as would consume little time, hence the instruments and methods of observation were necessarily of the simplest.

It is to be borne in mind, however, that at any given time the velocity and direction of the current are subject to the disturbing influences of prevailing meteorological conditions, and in many cases the effects of these disturbing influences are of greater magnitude than the quantities sought; also, when heavy seas prevail the observations must be made from a vessel which rolls and pitches. Under such conditions expensive instruments of high precision and refined methods of observation are clearly not of prime importance, and this is especially the case where a long series of observations is obtainable.

The apparatus employed for determining the velocity of the current was an adaptation of the old chip log, with which all sailors are familiar. For the purpose in hand, however, it was thought better to substitute a 15-foot pole for the customary log chip. This so-called current pole was made of white pine 2¾ inches in diameter and was weighted with sufficient sheet lead at one end to submerge 14 feet, so that only 1 foot floated out of water.

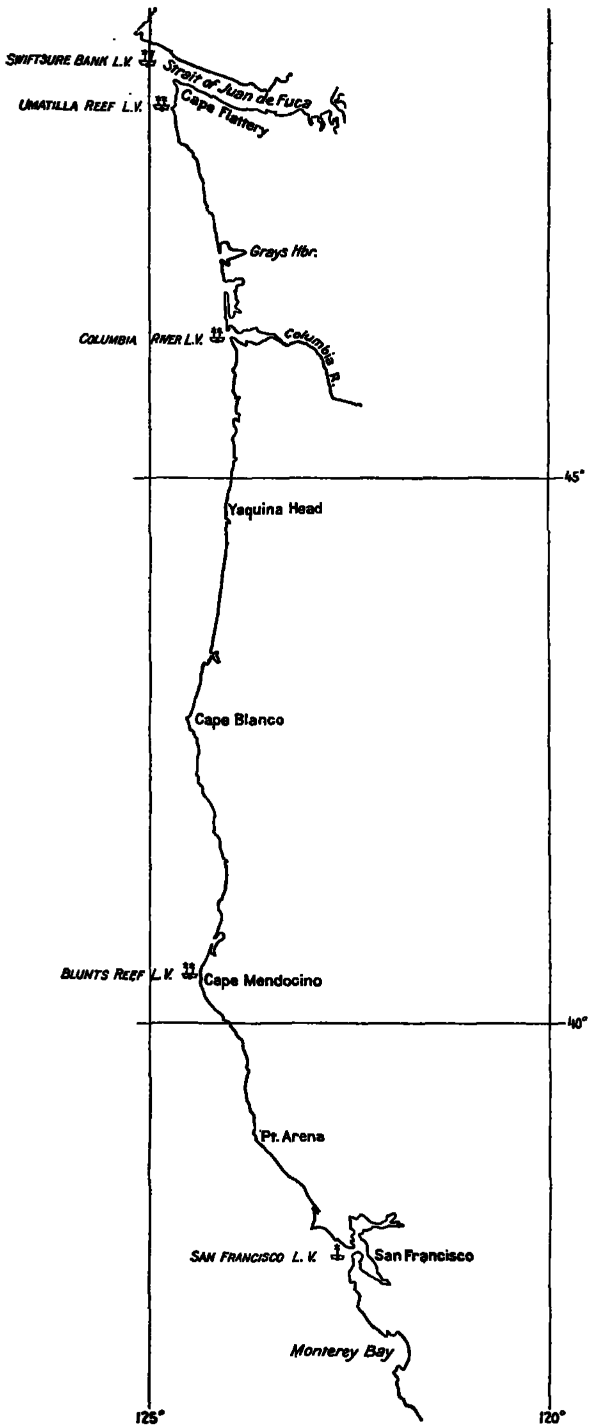

FIG. 1.—Locations of Pacific coast light vessels

The log line used was of lacing-cord twine, eleven sixty-fourths inch in diameter, and was marked in the customary manner for use with a 28-second sand glass. Later is was found advantageous to substitute stop watches for the sand glasses and to use log lines graduated for a run of one minute; that is, a length of 101 feet 4 inches of log line corresponded to a velocity of 1 nautical mile per hour, or 1 knot.

For determining the direction of the current use was made of a simple form of pelorus. This consisted of a circular brass disk 8 inches in diameter, graduated every 10°. It was fastened to the taffrail of the light vessel so that the 0° and 180° marks fixed a fore-and-aft line parallel to the keel of the ship. After the observer had let the current pole run out the observation interval for determining the velocity of the current he stretched the log line across the center of the pelorus and recorded the direction angle as indicated on the pelorus. This gave the angle the current made with the fore-and-aft line of the ship, which, with the compass heading of the ship at the same time, determined the direction of the current at that time.

Prior to 1917 observations had been made on the different light vessels for periods varying from three months to a year. In the fall of 1918 arrangements were made for securing continuous hourly observations covering a period of several years. While interruptions of several hours, due to severe gales, loss of current pole, or other untoward circumstances occur at times, the observations may be said to be practically continuous for the years 1919 and 1920. The manner of recording the observations and the items recorded are shown in the following copy of the current observations made on board San Francisco Light Vessel July 25, 1918. The compass bearings given in the columns "Ship heads" and "Wind direction" (fifth and six columns) are magnetic. The force of the wind is estimated in accordance with the Beaufort scale and is recorded in statute miles per hour.

TABLE 1.—*Current observations, San Francisco Light Vessel, July 25, 1919*

Time (standard, 105th meridian)	Current			Ship heads	Wind	
	Velocity		Direction		Direction	Force
	Knots	Tenths	On pelorus	Compass	Compass	
Midnight	0	8	10	NW x W	W	
1 a. m.	0	8	20	NW x N	W	
2 a. m.	1	1	20	NW x N	W	
3 a. m.	1	0	20	NW x N	W	
4 a. m.	1	0	10	NNW	W	
5 a. m.	0	8	30	N	W	
6 a. m.	1	3	350	ENE	W	
7 a. m.	1	2	350	SE x S	NW	
8 a. m.	1	1	340	S x E ¼ E	NW	
9 a. m.	1	0	350	S	NW	[illegible]
10 a. m.	0	9	350	S	NW	
11 a. m.	0	6	320	SW x S	NW	[illegible]
Noon	0	5	310	SW x W	WNW	18
1 p. m.	0	3	330	W x S	WNW	23
2 p. m.	0	2	330	W x S	WNW	23
3 p. m.	0	2	10	W x N	W	23
4 p. m.	0	5	20	W x N ½ N	W	28
5 p. m.	0	7	20	W x N	WSW	28
6 p. m.	0	8	20	WNW	W	28
7 p. m.	0	7	40	W x N ½ N	W	28
8 p. m.	0	3	50	W x N	W	28
9 p. m.	0	2	20	W x N	W	28
10 p. m.	0	0		W	W	23
11 p. m.	0	4	60	W x N	W	23

II. GENERAL CHARACTERISTICS OF TIDAL CURRENTS

TIDAL VS. NONTIDAL CURRENTS

Before entering into a detailed discussion of the currents at each of the light vessels on the Pacific coast it will be of advantage to review briefly some of the general characteristics of currents, taking up tidal currents first.

As occurring in nature, currents may conveniently be classified under two heads. There is, first, the tidal current which accompanies the rising and falling of the surface of the sea, due to the tides. Superimposed upon these tidal currents we find the second class of currents known by the general name of nontidal currents. These are brought about by a number of different agencies, such as fresh-water run-off, winds, differences in density of sea water, or other such causes. What chiefly distinguishes these two classes of currents from each other is the fact that tidal currents are periodic, partaking of the periodicity of the tides, while nontidal currents are not periodic.

The last statement may require some qualification. Nontidal currents due to winds or to fresh-water run-off exhibit fluctuations dependent upon the seasonal variation in prevailing winds and in amount of rainfall. While these may, therefore, be regarded as possessing a rough seasonal periodicity, they do not have the strictly periodic character exhibited by tides or tidal currents, which may be predicted accurately years in advance.

In the open sea and in inshore tidal waters these two classes of currents are found occurring together, tidal currents predominating in some places and nontidal in others. Tidal currents generally attain considerable velocity in narrow entrances to bays, in constricted parts of rivers, and in passages from one body of water to another. Thus, we find tidal currents attaining a velocity of 3 to 4 knots in the entrance to San Francisco Bay, 5 to 6 knots in Hell Gate, East River, and 8 to 10 knots or more in Seymour Narrows, British Columbia. Along the coast and farther offshore tidal currents are generally of moderate velocity, and in the open sea calculation based on the theory of wave motion gives a tidal current of less than one-tenth of a knot.

RECTILINEAR OR REVERSING CURRENTS

In a bay or river and, in general, where there is a restriction in width, the tidal current is of the rectilinear or reversing type; that is, the flood current runs in one direction for a period of about six hours and the ebb for a like period in the opposite direction. The change from flood to ebb gives rise to a period of slack water during which the velocity of the current is zero. An example of this type of current is shown in Figure 2, which represents graphically the hourly velocity and direction of the current as observed in New York Harbor on July 22, 1922. The upper curve represents the velocity of the current, the flood or north-going current being plotted above the axis of X and the ebb or south-going current below the axis of X. The lower curve represents the magnetic direction of the current.

The velocity curve presents, approximately, the form of the well-known sine or cosine curve. At midnight or the beginning of the day the current was running southerly or ebb, attaining its maximum velocity or strength of ebb about 1:30, after which it decreased gradually, slack water coming about 5 o'clock. The current now reversed its direction and entered on a cycle in the flood direction, gradually increasing in velocity for a period of about three hours, when it attained its maximum flood velocity or strength of flood and then decreasing in velocity for another period of three hours when slack water occurred.

In the lower curve of Figure 2 the direction of the current is given in degrees, north being 0°, east 90°, south 180° and west 270°. The directions are magnetic and represent the direction of the current as derived from hourly observations. The direction curve shows at once that in the rectilinear current the current flows in practically the same direction during the entire period of flood, with an abrupt change of about 180° at the time of slack water. For the ebb period the direction curve likewise shows the current to have been setting in the same direction for the entire period, with an abrupt change of about 180° at slack water.

ROTARY CURRENTS

Offshore the tidal currents are generally not of the rectilinear type. Instead of flowing in the same general direction during the

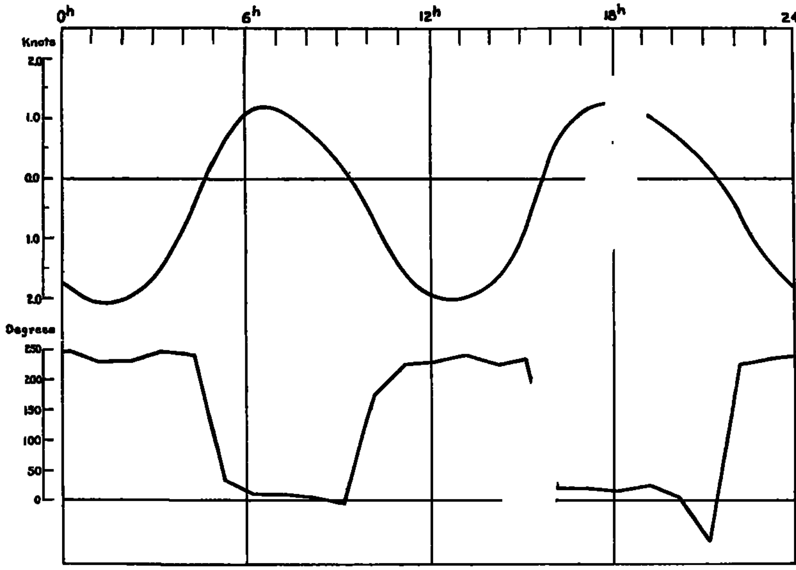

FIG. 2.—Rectilinear current, New York Harbor

entire period of the flood and in the opposite direction during ebb, the tidal currents offshore change direction continually. Such currents are therefore called rotary currents. An example of this rotary type of current is shown in Figure 3, which represents in diagrammatic form the velocity and direction of the current at the beginning of each hour of the afternoon on September 24, 1919, at Nantucket Shoals Light Vessel. This light vessel is stationed in 30 fathoms of water off the coast of Massachusetts about 40 miles southeasterly from Nantucket Island.

The current is seen to have changed its direction at each hourly observation, the rotation being in the direction of movement of the hands of a clock, or from north to south by way of east and then to north again by way of west. Beginning at noon the current was setting N. 69° E. with a velocity of 1 knot. At 1 p. m. the velocity of the current was 1.1 knots and the direction S. 45° E., and in the hours following we find the current constantly changing its direction clockwise, so that in a period of about 12 hours it has veered completely round the compass.

It will be noticed that the ends of the radii vectores, representing the velocities and directions of the current at the beginning of each hour, define a somewhat irregular ellipse. If a number of hourly

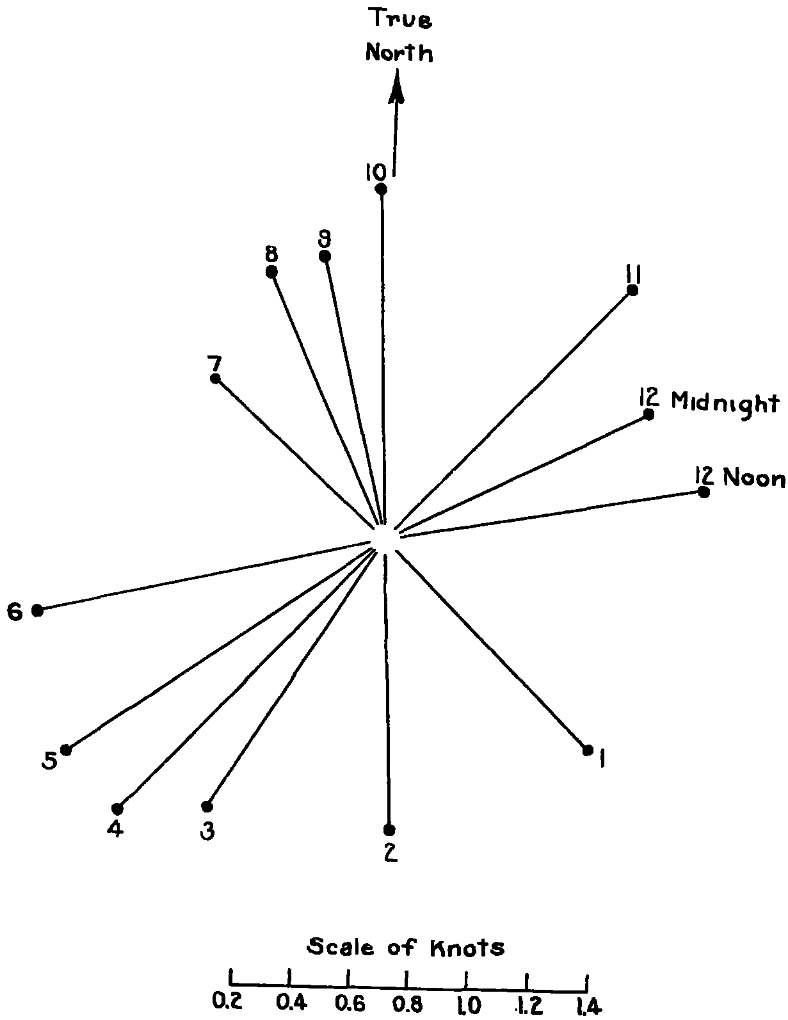

FIG. 3.—Rotary current, Nantucket Shoals Light Vessel

observations are averaged, thus eliminating accidental errors and temporary meteorological disturbances, the regularity of the curve will be considerably increased. Figure 4 represents the current curve for the same station, determined from hourly observations covering the month of July, 1920. Since the tidal or current day has a length of 24 hours 50 minutes, instead of the 24 hours of the civil or astronomical day, it is necessary, in averaging the hourly observed values of the current, to use aliquot parts of a day whose length is 24 hours 50 minutes. In many cases this can be most conveniently done by tabulating the observed hourly values of the

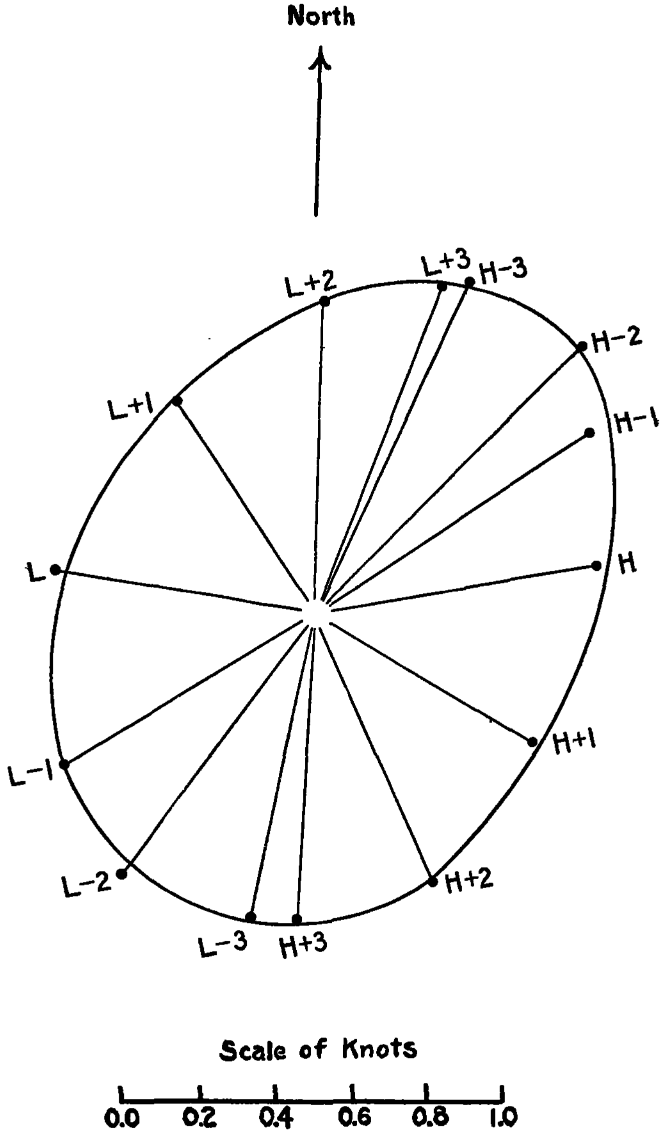

FIG. 4.—Mean current curve, Nantucket Shoals Light Vessel, July, 1920

current with reference to the times of high and low water at a near-by place. In the case of Figure 4, the hourly values of the current are referred to the times of high and low water at Boston, Mass.

From Figures 3 and 4 it is evident that in a rotary current there is no period of slack water when the velocity of the current is zero as in the rectilinear or reversing current. In the rotary type of tidal current the current is running at all times; but it will be noted that in each semidaily cycle there are two periods of maximum current and two periods of minimum current. These maxima and minimi correspond, respectively, to the major and minor semiaxes of the ellipse and may be taken as corresponding with the strengths and slacks of current of the rectilinear type.

VARIATION OF CURRENT WITH MOON'S CHANGING PHASES

Tides and tidal currents are different features of the same phenomenon which is brought about by the attraction of sun and moon upon the rotating earth, the tides being the vertical movement of the waters and the tidal currents the horizontal movement. The tidal current, therefore, presents many of the characteristics of the tide. Thus, we have the strongest currents when the moon is full and new and weakest currents when the moon is in its first and third quarters; also, when the moon has considerable declination, the currents, like the tides, exhibit the feature known as diurnal inequality.

As related to the moon's changing phases the variation in the strength of the current from day to day is approximately proportional to the corresponding change in the range of the tide. This is illustrated by a series of tidal and current observations made in the entrance to Delaware Bay in the month of April, 1919. During that month we find from a Nautical Almanac or from the Tide Tables for that year that new moon occurred on April 1, first quarter on the 7th, full moon on the 15th, and third quarter on the 23d. In order to minimize the effects of accidental errors, it will be of advantage to take the observations for groups of two days, using the day of the moon's phase given above and the day following. For those days the velocity of the current at strength and the range of the tide varied as shown in Table 2.

TABLE 2.—*Changes in tide and current, Delaware Bay, related to moon's phases*

Observations made—	Moon's phase	Tide at Breakwater Harbor, Del.		Current at Overfalls Light Vessel	
		Range	Change	Velocity	Change
		Feet	*Per cent*	*Knots*	*Per cent*
Apr. 1-2, 1919	New moon	5.78		2.14	
			−36		−25
Apr. 7-8, 1919	First quarter	3.72		1.61	
			+16		+20
Apr. 15-16, 1919	Full moon	4.30		1.94	
			−23		−14
Apr. 23-24, 1919	Third quarter	3.32		1.66	

The figures in the column headed "Change, per cent," which give the percentage increase or decrease of the range of the tide and the velocity of the current from one phase of the moon to the other, bring out the fact that, as related to the moon's changing phases, the velocity of the current at any given place and the range of the tide change in approximately the same proportion.

VARIATION OF CURRENT WITH CHANGE IN MOON'S DECLINATION

The response of the tide to changes in the declination of the moon, or its distance north or south of the Equator, gives rise to the feature known as the diurnal inequality. When the moon is over the Equator—when the declination of the moon is zero—there is very little difference between morning and afternoon high waters or between morning and afternoon low waters. As the moon moves north or south of the Equator the heights of the two high waters and also of the two low waters of the day begin to differ, this difference increasing with the increasing declination of the moon; and a little after the time of the moon's maximum north or south declination the difference between the two high waters or between the two low waters is greatest.

As related to the moon's changing phases, the change in the current was found to be approximately proportional to the corresponding change in the range of the tide, but in regard to the moon's changing declination tide and current do not respond alike, the diurnal variation in the tide at any place generally being greater than the diurnal variation in the current. As an example, we may take the tidal and current observations made in Delaware Bay during the month of July, 1919. For that month we find from the Nautical Almanac or from the Tide Tables that the moon was on the Equator on the 3d, farthest south on the 10th, again on the Equator on the 17th, and farthest north on the 23d. If, as before, we use groups of two days to minimize accidental errors, the changes in tide and current in response to the moon's changing declination are as follows:

TABLE 3.—*Changes in tide and current, Delaware Bay, related to moon's declination*

Observations made—	Moon's declination	Tide at Delaware Breakwater, Del.						Current at Overfalls Light Vessel, off Delaware Bay					
		High water			Low water			Flood			Ebb		
		A. M.	P. M.	Ineq.	A. M.	P. M.	Ineq.	A. M.	P. M.	Ineq.	A. M.	P. M.	Ineq.
		Feet	*Feet*	*P. ct.*	*Feet*	*Feet*	*P. ct.*	*Knots*	*Knots*	*P. ct.*	*Knots*	*Knots*	*P. ct.*
July 3-4, 1919	Zero	5.75	5.70	3	1.80	2.20	22	2.00	1.80	10	2.00	2.10	5
July 10-11, 1919	South	4.50	6.00	80	1.50	1.50	0	1.50	2.20	39	1.70	1.80	6
July 17-18, 1919	Zero	5.55	5.75	9	1.15	1.40	11	2.00	2.00	0	2.10	2.30	10
July 23-24, 1919	North	5.20	6.45	63	1.00	1.20	8	2.00	2.30	13	2.50	2.80	13

In the table above the diurnal inequality for both current and tide is given as a ratio. For the current it is the ratio of the difference in velocity of the two floods or two ebbs of the day to the mean of the flood and ebb strengths of current for the day in question, while for the tide it is the ratio of the difference in height of the two high waters or two low waters to the half range of the tide for the day in question. The four columns headed "Ineq. P. ct.," which give the percentage inequality, show that the inequality in the tide increases very much more from the moon's zero declination to maximum north or south declination than does the current during the same time.

THEORETICAL RELATION OF VELOCITY OF CURRENT TO RANGE OF TIDE

The relations subsisting between the changes in the velocity of the current at any given place and the range of the tide at that place, discussed in the two preceding sections, may be derived from general considerations of a theoretical nature. For the sake of simplicity let us assume a harbor whose area S is constant from low water to high water, connected with the sea by a rectangular opening having a width F and a depth D reckoned from mean sea level. Let $W_0=$ volume of water in the harbor below the plane of mean sea level, $R=$range of tide, and let time be reckoned from the instant of mean sea level. Then, if at any time t, the total volume of water, is represented by W, the velocity of the current through the opening by v, and the height of the tide from mean sea level by y, we have

$$W=W_0+S\,y \qquad (1)$$

$$dW=vF(D+y)dt \qquad (2)$$

and from (2) we get

$$v=\frac{1}{F(D+y)}\cdot\frac{dW}{dt} \qquad (3)$$

Expressing y in the harmonic notation we have

$$y=A\cos(at+\alpha)+B\cos(bt+\beta)+C\cos(ct+\gamma)+\ldots \qquad (4),$$

where A, B, C are the amplitudes, a, b, c the speeds, and α, β, γ the initial phases of the harmonic tidal components. From (4) and (1) we get

$$\frac{dW}{dt}=-S[A\,a\sin(at+\alpha)+B\,b\sin(bt+\beta)+C\,c\sin(ct+\gamma)+\ldots]$$

which in (3) gives

$$v=-\frac{S[A\,a\sin(at+\alpha)+B\,b\sin(bt+\beta)+C\,c\sin(ct+\gamma)+\ldots]}{F(D+y)} \qquad (5)$$

Now, y varies in value from $-\frac{1}{2}R$ to $+\frac{1}{2}R$, and, as compared with D or the depth, $\frac{1}{2}R$ is generally small; hence (5) may be written, approximately,

$$v=-\frac{S}{FD}[A\,a\sin(at+\alpha)+B\,b\sin(bt+\beta)+C\,c\sin(ct+\gamma)+\ldots]$$

$$=-\frac{S}{FD}[A\,a\cos(at+\alpha-90^\circ)+B\,b\cos(bt+\beta-90^\circ)+C\,c\cos(ct+\gamma-90^\circ)+\ldots] \qquad (6)$$

and from (6) it follows that the amplitudes of the harmonic current components are related to each other, not as the amplitudes of the corresponding tidal components, but very nearly as the latter multiplied by their speeds.

The ratio of the spring range to the neap range of the tide is given approximately by

$$\frac{2(M_2+S_2)}{2(M_2-S_2)} \qquad (7),$$

hence the strengths of the current at times of spring and neap tides should be to each other as

$$\frac{m_2M_2+s_2S_2}{m_2M_2-s_2S_2} \tag{8}$$

where s_2 and m_2 are the speeds, respectively, of S_2 and M_2. But s_2 and m_2 do not differ much, being, respectively 30°.00 and 28°.98 per mean solar hour; therefore, (8) may be written approximately $\frac{s_2(M_2+S_2)}{s_2(M_2-S_2)}$, which is identical with (7). It follows, therefore, that the change in the velocity of the current from springs to neaps should be approximately proportional to the corresponding change in the range of the tide.

As regards the change in response to the changing declination of the moon, we may write the diurnal inequality of the tide at the time of the moon's greatest declination in the harmonic notation

$$\frac{[M_2+(K_1+O_1)]-[M_2-(K_1+O_1)]}{M_2}=\frac{2(K_1+O_1)}{M_2} \tag{9}$$

and hence for the currents,

$$\frac{2(k_1K_1+o_1O_1)}{m_2M_2} \tag{10}$$

The values of m_2, k_1, and o_1 per mean solar hour are, respectively, 28°.98, 15°.04, and 13°.94. Now, k_1 and o_1 do not differ greatly and $m_2=k_1+o_1$; we may therefore write (10) approximately

$$\frac{2\frac{m_2}{2}(K_1+O_1)}{m_2\ M_2}=\frac{K_1+O_1}{M_2} \tag{11}$$

From (9) and (11) it therefore follows that the diurnal inequality in the current at any place is approximately half of what it is in the tide.

ROTARY CURRENTS AND CHANGES IN MOON'S PHASE AND DECLINATION

In the preceding sections the response of the current to changes in the phase and declination of the moon was illustrated by examples and considerations chosen from rectilinear currents. The rotary currents likewise show similar responses to changes in the moon's phase and declination. This is brought out in Figure 5, in which the hourly velocity and direction of the current at Nantucket Shoals Light Vessel at various times in the month of July, 1920, is represented graphically.

The hourly velocities and directions of the current have been referred to the times of high and low water at Boston, *H* referring to the time of high water and *L* to the time of low water. The average hourly velocity and direction of the current at Nantucket Shoals Light Vessel for the month of July, 1920, as determined from continuous observations from July 1 to 29, inclusive, is represented in Figure 4. On July 9 the moon was in its third quarter and on the 23d in its first quarter, and the diagram in the upper left-hand corner shows that on those days the currents were weaker than the average. On the 1st of July the moon was full and on the 16th new. The diagram in the upper right-hand corner, which represents the current conditions on those days, shows that the currents then were stronger than the average.

The two lower diagrams represent the hourly velocity and direction of the current on the days when the moon was over the Equator

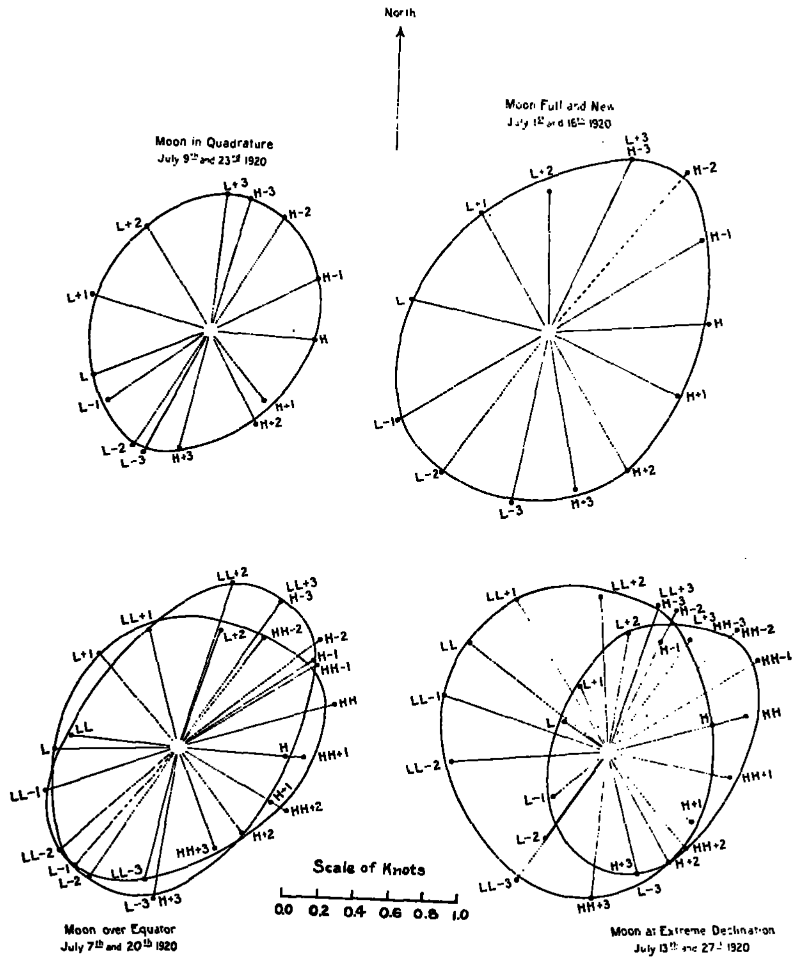

FIG. 5.—Current curves, Nantucket Shoals Light Vessel, July, 1920

and again when it was farthest north and south. In order to bring out the differences between the currents in the morning and those in the afternoon distinction is made between lower high water and higher high water and between lower low water and higher low water. In the two diagrams in question, *H* and *HH* refer, respectively, to lower high water and to higher high water at Boston, while *L* and *LL* refer, respectively, to higher low water and to lower low water at the same place.

The lower left-hand diagram shows that on July 7 and 20, when the moon was over the Equator, the currents in the morning did not differ greatly from those in the afternoon, as evidenced by the fact that the two ellipses representing morning and afternoon currents are quite similar. On July 13 the moon attained its maximum north declination for the month and on the 27th its greatest south declination, and the diagram in the lower right-hand corner of Figure 5 shows that on these days the currents in the morning differed very considerably from those of the afternoon.

As regards the change in the tidal current in response to the changing declination of the moon, it is evident that since tides and tidal currents are intimately related the diurnal inequality in the currents will be greater in regions where the tides exhibit this inequality to a marked degree. On the Pacific coast the diurnal inequality in the tides is very much greater than on the Atlantic coast, and hence we should expect to find the currents, too, exhibiting this feature to a greater extent than on the Atlantic coast. This is borne out by the observations made on the Pacific coast light vessels as is shown in the succeeding sections.

EFFECT OF NONTIDAL CURRENTS

The tidal current is subject to the disturbing influences of nontidal currents which affect the regularity of its occurrence as regards time, velocity, and direction. In the case of the rectilinear current the effect of a nontidal current is, in general, to make both the periods and the velocities of flood and ebb unequal and to change the times of slack water, but to leave unchanged the times of flood and ebb strengths. This is evident from a consideration of Figure 6, which represents a simple rectilinear tidal current, the time axis of which is the line *A B*, flood velocities being plotted above the line and ebb velocities below.

When unaffected by nontidal currents, the periods of flood and ebb and the velocities at times of strength of flood and strength of ebb are, in general, equal as represented in the diagram, and slack water occurs regularly three hours and six minutes after the times of flood and ebb strength. But suppose a steady nontidal current is introduced which has a velocity component, represented by the line *C D*, in the direction of the tidal current. It is evident that the strength of ebb will be increased by an amount equal to *C D*, while the flood strength will be decreased by the same amount. The current conditions may now be completely represented by drawing as a new time axis the line *E F* parallel to *A B* and distant from it the length *C D*.

The period of flood which in the unaffected tidal current was equal to the period of ebb has been reduced and the period of the ebb has been increased. The time of slack water before flood has, therefore, become later, while the time of slack before ebb has become earlier; the times of flood and ebb strength, however, remain unchanged.

It is evident that if the velocity of the nontidal current exceeds the velocity of the tidal current at time of strength the tidal current will be completely masked, and the resultant current will set at all times in the direction of the nontidal current. Thus, if the line *O P* represents the velocity component of the nontidal current in the direction of the tidal current, the new time axis will be the line *G H*, and the current will be flowing at all times in the ebb direction. There will be no slack waters; but at periods 6 hours 12 minutes apart there will occur minimum and maximum velocities represented by the lines *R S* and *T U*, respectively.

In so far as the effect of the nontidal current on the direction of the rectilinear tidal current is concerned, it is only necessary to remark that the resultant current will set in a direction which at any time is the resultant of the tidal and nontidal currents at that time. The resultant direction and also the resultant velocity may be determined either graphically by the parallelogram of velocities or by the usual trigonometric computations.

Upon rotary currents the effects of a nontidal current are similar to those discussed in relation to rectilinear currents. These effects may most conveniently be studied diagrammatically.

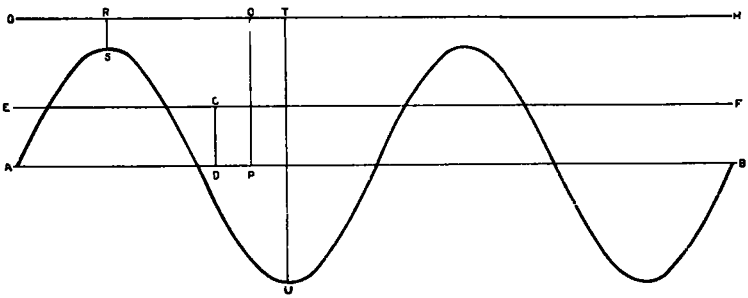

FIG. 6.—Effect of nontidal current on rectilinear current

In Figure 7 the left-hand diagram gives the hourly values of the current at Frying Pan Shoal Light Vessel, off the coast of North Carolina, as referred to the times of tide at Charleston, S. C., for the period July 14 to 20, 1920. During this period the wind was blowing from the southwest practically all the time with an average velocity of about 20 miles per hour. The lines drawn from *P* to the various points give the velocity and direction of the current at each tidal hour, and while during the entire period the wind current completely masked the tidal current, since at all times the current was setting easterly, the plotting clearly brings out the rotary tidal current.

The right-hand diagram of Figure 7 represents the current at the same station during the period January 29 to February 2, 1920, when the wind was blowing from the northeast with an average velocity of about 30 miles per hour. This produced a nontidal current setting southwesterly, which so completely masked the tidal current that at all times during this period the current was setting southwesterly; but the plotting, as in the previous case, brings out clearly the rotary tidal current. It is interesting to note that, although the observations were made under the disturbed conditions brought about by the strong winds, nevertheless the curves representing the tidal currents show marked similarity in time, direction, and velocity of current.

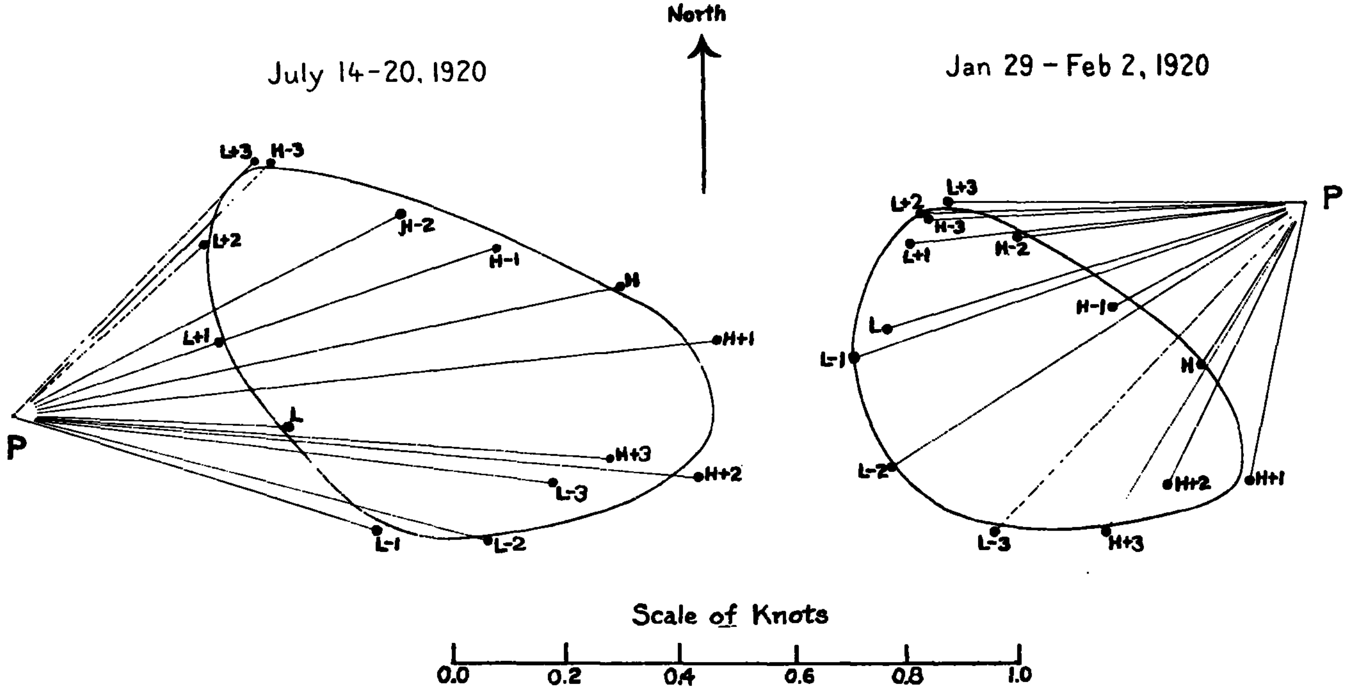

FIG. 7.—Effect of nontidal current on rotary current

In the rotary tidal current it is evident from the foregoing that the effect of a nontidal current may be determined by shifting the center of figure a distance which represents the velocity and direction of the nontidal current and drawing lines from this new origin to the ends of the radii victores of the rotary tidal current. These lines, then, give by their lengths and directions the velocity and direction of the resultant current at the different hours.

RELATION OF TIME OF CURRENT TO TIME OF TIDE

Theoretically, the times of maximum flood and ebb currents, or the strengths of flood and ebb, should occur at the times of high and low water in a progressive wave and midway between high and low waters in a stationary wave. The times of slack water should occur midway between high and low water in a progressive wave and at the times of high and low water in a stationary wave. In other words, in simple wave motion the time of current has a constant and simple relation to the time of tide.

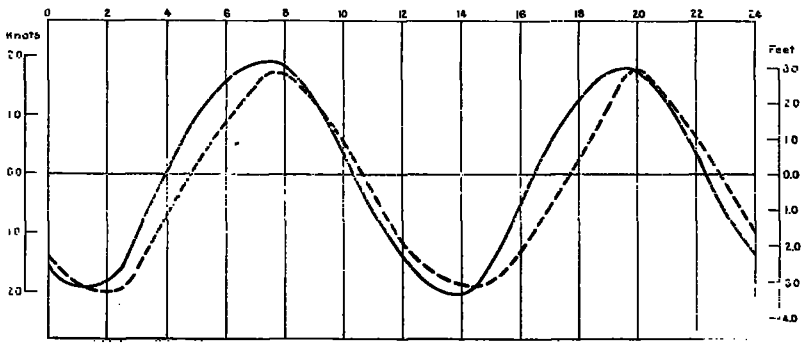

FIG. 8.—Tide and current curves, New York Harbor

While simple wave motion is rarely found in the tidal movements of the waters near the coast, it is very convenient in the study of the currents to refer the times of current to the times of tide; and where the diurnal inequality in the tide is small, as is the case on the Atlantic coast, the relation between the time of current and the time of tide is very nearly constant. This is brought out in Figure 8, which represents the curves of the current and of the tide in New York Harbor on October 9, 1919, the current curve being the dashed-line curve and the tide curve being the full-line curve.

The curves of Figure 8 were drawn by plotting the heights of the tide and the velocities of the current to the same time scale and to such velocity and height scales as would make the maximum ordinates of the two curves approximately equal. The time axis, or axis of X, represents the line of zero velocity for the currents and of mean sea level for the tides, the velocity of the current being plotted in accordance with the scale of knots on the left, while the height of the tide, reckoned from mean sea level, was plotted in accordance with the scale of feet on the right.

From Figure 8 it is evident that the corresponding features of tide and current in New York Harbor bear a very nearly constant time relation to each other, and this permits the times of slack and of strength of current to be referred to the times of high and low water. Thus, the strength of ebb occurred about 0.6 hour after the time of low water, both morning and afternoon, slack before flood occurred 2.2 hours before high water, strength of flood 0.4 hour after high water, slack before ebb, 3 hours before low water. It is to be noted in this connection that these time relations, which for the various phases of the current are approximately constant, are subject to variations brought about by nontidal currents, the disturbing effects of which were considered in the previous section.

The velocity and direction of rotary currents in regions where the diurnal inequality in the tide is small may likewise be referred to the time of tide. Examples of such reference are given in Figures 3, 4, and 5, which bring out the very nearly constant time relationship between tide and current.

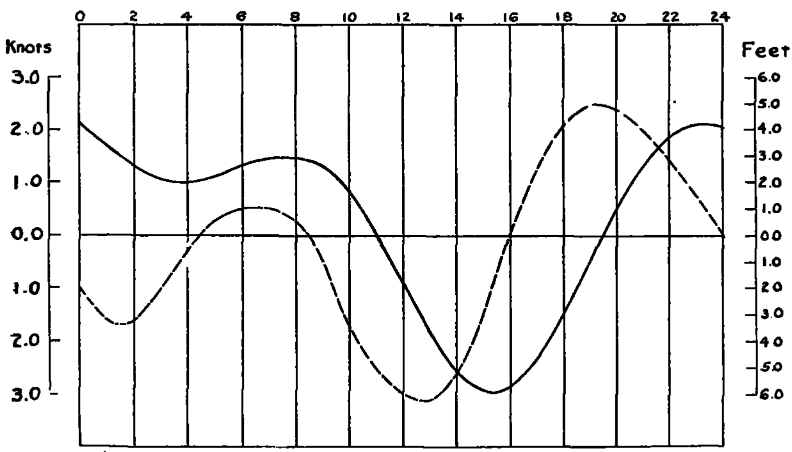

FIG. 9.—Tide and current curves, Puget Sound

Where the diurnal inequality in the tide is considerable, the time relations between tide and current are subject to considerable variation, apart from the disturbing effects of nontidal currents. This is due to the fact, previously mentioned, that the diurnal inequality in the current is only about half as great as in the tide. This brings about differences in the corresponding features of tide and current as between morning and afternoon. Figure 9, which represents simultaneous tide and current curves in Puget Sound, Wash., shows the relationship between tide and current in a locality of considerable diurnal inequality.

In Figure 9 the dashed-line curve is the velocity curve of the current in Rich's Passage, Puget Sound, Wash., as observed on March 29, 1917; the full-line curve is the tide curve for the same day at Seattle, also in Puget Sound. Here we find no such correspondence between tide and current curves as exhibited in Figure 8, although the scales of heights and velocities were adjusted in a similar manner.

The diurnal inequality of the tide in Puget Sound is exhibited principally in the low waters, and the currents reproduce this inequality, but in a lesser degree, and because of this difference of inequality in tide and current the time relations between tide and current do not show the constancy found in Atlantic waters. Thus, the time of flood strength as related to the time of high water shows wide variation as between morning and afternoon. In the morning the strength of flood occurred 1.4 hours before high water at Seattle, while the afternoon strength of flood occurred 3.9 hours before high water, giving a difference between the two of 2.5 hours.

The greatest divergence in the time relations between currents and tides characterized by diurnal inequality occurs, obviously, when the diurnal inequality is at a maximum; that is, when the moon has its greatest north or south declination. The example given in the preceding paragraph was purposely chosen on the day when the moon was at its greatest north declination. At the same station a week later—on April 5, 1917—when the moon was over the Equator, the time relation between current and tide was characterized by very much greater constancy. On that day the strength of flood in the morning occurred 2.4 hours before high water and in the afternoon 2.6 hours before high water.

In the case of rotary currents in regions of considerable diurnal inequality, the time relations between tide and current are subject to the variations discussed in the previous paragraph. The fact that it is generally necessary to refer the rotary currents to the tide some distance away (for it is a somewhat difficult matter to make tidal observations off shore) introduces further complications. Nevertheless, the referring of the current to the time of tide is the most convenient method of specifying the current whether rotary or rectilinear.

TABULATION OF CURRENT OBSERVATIONS

With rectilinear currents, the most convenient method of treating the observations consists in plotting the velocities of the current to a suitable scale on cross-section paper, the flood being plotted above the axis of X and the ebb below, and it is then a simple matter to draw a curve through the plotted points. The maximum and minimum points of this curve then specify the flood and ebb strengths of the current both as to time and velocity, and the points in which the curve cuts the axis of X determine the times of slack water. Examples of such plottings are shown in Figures 2, 8, and 9. The very great advantage of this graphic method lies in the fact that errors in the observations may easily be detected and smoothed out, whether these errors be due to the rolling of the ship, to the disturbing effects of wind and weather, or to other causes. There is the further advantage, also, that by this method short breaks in the observations may easily be interpolated.

After the observations have been plotted the times of slack and the times and velocities of the strength of the current may then be entered into a form similar to that shown below. The times of strength of current now being specified, the direction of the current at these times may then be determined, by interpolation, directly from the record book and entered into the appropriate columns. The times of high and low water at some near-by place are then entered into the column on the left and the intervals between tide and current determined. Where no simultaneous tidal observations are at hand, the predicted times of high and low waters may be used.

In the case of a short series of observations, the mean velocities derived from such a tabulation may be corrected by the ratio of the mean range of the tide to the range of the tide for the days in question, employing for the purpose the tide at some near-by place. With a series of observations extending over several months, the most satisfactory method is to tabulate in groups of 29 days and then to derive a mean from these 29-day groups. A tabulation, as outlined above, of the current observations made on board Ram Island Reef Light Vessel, in Long Island Sound, during the month of September, 1915, is shown in Table 4.

TABLE 4.—*Tabulation of current strengths and slacks*

Station, Ram Island Reef Light Vessel. Latitude, 41° 18′ 02″ N.; longitude, 71° 58′ 28″ W.
[Referred to time of tide at New London, Conn.]

Date	Time of—						Current referred to tide				Strength of flood		Strength of ebb	
	High water	Low water	Slack before flood	Strength of flood	Slack before ebb	Strength of ebb	Slack before flood	Strength of flood	Slack before ebb	Strength of ebb	Direction mag.	Velocity	Direction mag.	Velocity
1915	*H.*	*H.*	*H.*	*H.*	*H.*	*H.*	*H.*	*H.*	*H.*	*H.*	*Deg.*	*Knots*	*Deg.*	*Knots*
Sept. 1	2.6	8.9	9.4	0.2	4.0	6.7	L+0.5	H−2.4	H+1.4	L−2.2	267	1.0	108	1.2
	15.0	22.0	23.0	12.6	16.5	19.1	1.0	2.4	1.5	2.9	278	1.2	129	1.3
2	3.7	9.8	11.0	1.8	5.0	7.5	1.2	1.9	1.3	2.3	271	1.0	110	1.2
	16.0	22.9	23.8	13.7	17.0	20.1	.9	2.3	1.0	2.8	282	1.0	102	1.2
3	4.7	10.8	12.0	2.6	6.0	8.8	1.2	2.1	1.3	2.0	281	1.0	96	1.2
	17.0	23.8	-----	15.0	18.0	21.4	--------	2.0	1.0	2.4	333	1.0	98	1.4
4	5.7	11.7	1.0	3.3	7.0	9.8	1.2	2.4	1.3	1.9	289	1.0	105	1.4
	17.9	-----	13.0	16.2	19.0	21.7	1.3	1.7	1.1	2.9	275	1.0	97	1.4
5	6.4	.6	2.0	4.3	7.6	11.1	1.4	2.1	1.2	1.4	281	1.1	94	1.4
	18.6	12.5	14.0	16.8	19.6	23.2	1.5	1.8	1.0	2.0	279	1.2	96	1.5
6	7.1	1.2	2.0	5.2	8.5	11.7	.8	1.9	1.4	1.6	285	1.2	95	1.4
	19.3	13.3	14.8	17.5	20.6	23.8	1.5	1.8	1.3	1.4	278	1.3	101	1.4
7	7.8	1.9	3.0	6.0	9.4	12.1	1.1	1.8	1.6	1.9	276	1.3	101	1.4
	20.0	14.0	15.0	18.0	21.6	-----	1.0	2.0	1.6	------	278	1.2	------	------
8	8.4	2.5	4.0	6.5	9.6	.0	1.5	1.9	1.2	2.5	281	1.3	101	1.4
	20.6	14.7	16.0	18.6	22.3	12.4	1.3	2.0	1.7	2.3	274	1.3	105	1.4
9	9.0	3.1	4.0	7.5	10.6	.3	.9	1.5	1.6	2.8	270	1.4	98	1.7
	21.3	15.4	16.8	19.4	22.6	13.2	1.4	1.9	1.3	2.2	274	1.5	101	1.7
10	9.6	3.7	5.0	7.8	11.4	1.1	1.3	1.8	1.8	2.6	270	1.4	101	1.8
	21.9	16.2	17.4	20.3	23.4	14.2	1.2	1.6	1.5	2.0	262	1.5	107	1.7
11	10.3	4.3	5.6	9.0	11.8	1.9	1.3	1.3	1.5	2.4	264	1.3	106	1.7
	22.6	16.9	18.0	20.8	-----	14.3	1.1	1.8	--------	2.6	274	1.4	102	1.7
12	11.0	5.0	6.0	9.2	.4	2.4	1.0	1.8	1.8	2.6	272	1.5	106	1.6
	23.4	17.8	19.0	21.4	12.4	15.2	1.2	2.0	1.4	2.6	277	1.4	97	1.8
13	11.8	5.7	7.0	9.7	1.0	3.6	1.3	2.1	1.6	2.1	277	1.4	96	1.5
	-----	18.7	20.0	22.5	13.4	16.0	1.3	1.7	1.6	2.7	278	1.5	95	1.6
14	.2	6.6	8.0	11.0	1.6	4.4	1.4	1.7	1.4	2.2	281	1.4	96	1.4
	12.7	19.6	21.0	23.9	14.2	17.2	1.4	1.3	1.5	2.4	274	1.3	98	1.6
15	1.2	7.6	9.0	11.5	2.6	5.3	1.4	1.2	1.4	2.3	274	1.3	97	1.5
	13.7	20.7	22.0	-----	15.0	18.4	1.3	--------	1.3	2.3	------	------	100	1.8
16	2.3	8.7	10.6	.6	3.6	7.0	1.9	1.7	1.3	1.7	272	1.2	101	1.5
	14.8	21.8	23.5	13.2	16.5	19.6	1.7	1.6	1.7	2.2	281	1.2	97	1.5
17	3.5	9.8	11.8	2.0	5.0	8.0	2.0	1.5	1.5	1.8	276	1.2	101	1.5
	16.0	22.8	-----	14.2	17.5	20.4	--------	1.8	1.5	2.4	281	1.2	99	1.4
18	4.7	11.0	.0	3.2	6.4	9.2	1.2	1.5	1.7	1.8	275	1.2	111	1.3
	17.2	23.8	12.8	15.6	18.6	21.3	1.8	1.6	1.4	2.5	282	1.3	87	1.5

TABLE 4.—*Tabulation of current strengths and slacks*—Continued

Date	Time of—						Current referred to tide				Strength of flood		Strength of ebb	
	High water	Low water	Slack before flood	Strength of flood	Slack before ebb	Strength of ebb	Slack before flood	Strength of flood	Slack before ebb	Strength of ebb	Direction mag.	Velocity	Direction mag.	Velocity
1915	*H.*	*H.*	*H.*	*H.*	*H.*	*H.*	*H.*	*H.*	*H.*	*H.*	*Deg.*	*Knots*	*Deg.*	*Knots*
Sept. 19	5.8	12.0	1.0	4.1	7.5	10.1	1.2	1.7	1.7	1.9	291	1.2	107	1.3
	18.2	-----	13.6	16.4	20.0	22.9	1.6	1.8	1.8	1.8	278	1.4	98	1.6
20	6.7	.7	2.0	5.0	8.0	10.8	1.3	1.7	1.3	2.1	281	1.4	95	1.6
	19.0	12.9	14.6	16.5	20.6	23.2	1.7	1.5	1.6	1.5	293	1.4	93	1.7
21	7.5	1.5	3.0	6.0	9.0	12.3	1.5	1.5	1.5	1.5	276	1.6	68	1.5
	19.9	13.8	15.4	18.5	21.0	-----	1.6	1.4	1.1	-----	253	1.3	-----	-----
22	8.2	2.2	3.6	6.8	9.8	.2	1.4	1.4	1.6	2.0	263	1.3	104	1.6
	20.6	14.6	16.2	19.1	22.4	12.8	1.6	1.5	1.8	1.8	261	1.4	105	1.6
23	8.9	2.9	4.2	7.2	10.5	.6	1.3	1.7	1.6	2.3	268	1.3	102	1.5
	21.3	15.4	17.0	20.0	23.2	13.0	1.6	1.3	1.9	2.4	281	1.4	101	1.7
24	9.6	3.6	5.0	7.8	11.0	1.6	1.4	1.8	1.4	2.0	278	1.4	90	1.7
	22.0	16.2	17.6	20.5	23.4	14.1	1.4	1.5	1.4	2.1	280	1.5	101	1.7
25	10.3	4.2	5.8	8.3	11.6	1.8	1.6	2.0	1.3	2.4	264	1.4	102	1.6
	22.7	16.9	18.0	21.0	-----	14.6	1.1	1.7	-----	2.3	287	1.4	96	1.6
26	10.9	4.9	6.3	9.0	.0	3.1	1.4	1.9	1.3	1.8	294	1.4	89	1.7
	23.4	17.7	19.6	22.0	12.0	15.2	1.9	1.4	1.1	2.5	256	1.0	86	1.8
27	11.6	5.6	7.0	9.8	.2	3.2	1.4	1.8	.8	2.4	250	1.3	111	1.4
	-----	18.5	19.8	22.1	13.0	15.7	1.3	2.1	1.4	2.8	252	1.2	102	1.6
28	.2	6.4	8.0	10.4	1.4	4.1	1.6	2.0	1.2	2.3	269	1.3	97	1.4
	12.4	19.4	20.4	23.4	13.4	16.6	1.0	1.6	1.0	2.8	260	1.0	106	1.4
29	1.0	7.3	9.0	11.9	2.0	5.1	1.7	1.4	1.0	2.2	243	1.1	102	1.4
	13.3	20.4	21.0	23.9	14.6	17.6	.6	2.1	1.3	2.8	277	1.2	106	1.4
Sum	-----	-----	-----	-----	-----	-----	74.7	100.7	78.8	124.4	15,677	72.6	5,595	84.8
Divisor	-----	-----	-----	-----	-----	-----	56	57	56	56	57	57	56	56
Mean	-----	-----	-----	-----	-----	-----	L+1.33	H−1.77	H+1.41	L−2.22	275	1.27	100	1.51

The current observations in the case of a rectilinear current may also be treated by the harmonic method, the process being analogous in all respects to that employed in the harmonic treatment of tidal observations. The strength of flood is generally taken to correspond with high water and the strength of ebb with low water, and a constant is added to the hourly velocities of the current to change the negative values of the ebb current into positive values.

With rotary currents a convenient method of tabulating the observations consists in referring the hourly values of both velocity and direction to the times of high and low water at some near-by point and deriving a mean for the various hours.

With a series of observations extending continuously over a month or more it is generally sufficient to take the times of high and low water to the nearest hour. This makes possible the use of the hourly values of the velocity and direction of the current as observed and obviates the necessity of tedious interpolations. This method is exemplified in the tabulation below of observations made on board Nantucket Shoals Light Vessel from May 1 to 4, 1920.

TABLE 5.—*Tabulation of rotary current observations*

[Currents, Nantucket Shoals Light Vessel; referred to predicted tides at Boston; directions, magnetic]

Date	Hours before high water						High water		Hours after high water					
	3		2		1		0		1		2		3	
	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.
May 1, 1920	0.8	356	0.9	29	1.0	40	0.6	52	0.4	124	0.6	142	0.7	212
	.9	385	.8	69	.4	90	.2	101	.2	124	----	----	----	----
May 2, 1920	1.0	365	1.0	28	1.0	81	.6	91	.4	114	.4	168	.6	190
	.4	385	.8	46	.9	68	.4	112	----	----	.4	145	.6	166
May 3, 1920	.8	368	.8	19	.4	46	.2	135	.2	135	.3	180	.5	224
	.6	392	1.0	45	1.0	68	----	----	.4	215	.5	256	.8	266
May 4, 1920	.8	382	1.0	44	.8	44	.6	78	.4	122	.6	194	.8	238
	.4	356	.6	56	.6	149	.8	65	.6	95	.6	125	.8	195
Sum	5.7	2,989	6.9	336	6.1	586	3.4	634	2.6	929	3.4	1,210	4.8	1,491
Mean	.71	374	.86	42	.76	73	.49	91	.37	133	.49	173	.69	213

Date	Hours before low water						Low water		Hours after low water					
	3		2		1		0		1		2		3	
	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.
May 1, 1920	0.4	258	0.6	280	0.7	302	0.7	325	0.7	335	0.7	346	0.8	−4
	.7	212	.8	245	.8	245	.6	266	.6	299	.8	362	.9	25
May 2, 1920	.6	201	.8	224	.8	235	.8	258	.7	314	.7	232	1.0	5
	.6	166	.7	200	.7	211	.7	279	.6	290	.6	232	.4	25
May 3, 1920	.6	246	.6	258	.6	280	.5	291	.5	314	.5	325	.8	8
	.8	266	.9	268	.6	278	.6	280	.6	315	.4	349	.6	32
May 4, 1920	.8	238	.9	270	.8	291	.7	325	.6	348	.8	382	.8	22
	.8	195	.8	255	.6	221	.6	241	.2	352	.1	348	.4	−4
Sum	5.3	1,782	6.1	2,000	5.6	2,063	5.2	2,265	4.5	2,567	4.6	2,576	5.7	109
Mean	.66	223	.76	250	.70	258	.65	283	.56	321	.58	322	.71	14

It is to be noted that in the method of tabulation outlined for rectilinear currents the velocities of the current are treated as scalar quantities, since the flood may be considered as setting at all times in the same direction, and likewise the ebb; but in the hourly tabulation of rotary currents we are dealing with vector quantities. Hence this method of tabulation may be employed only when the directions of the current in each hourly column do not differ greatly, and even in such cases care must be taken to add or subtract 360° to the direction of the current where necessary. The necessity for this is evident from an inspection of the last two columns of the foregoing tabulation for Nantucket Shoals Light Vessel.

Where the rotary tidal current is weak, or where the disturbing effects of nontidal currents are such as to modify considerably the normal tidal currents, the hourly tabulation of the velocity and direction of the current becomes unsatisfactory and recourse must be had to some vector method. A convenient one consists in resolving the hourly velocities of the current into two directions perpendicular to each other, generally north-and-south and east-and-west. This resolution may be accomplished very expeditiously by the use of graphic tables, and the resolved velocities may then be tabulated hourly with reference to the times of high and low water at some near-by place. To obviate the necessity of employing negative quantities a constant is added to the resolved velocities to make all the values positive, this constant being entered into the graphic resolution tables, so that the resolved velocities with the constant added may be taken directly, by inspection, from the graphic tables.

The harmonic analysis may also be employed for rotary currents. After the resolutions have been performed, as above, two sets of hourly tabulations are made, one for the north-and-south direction and the other for the east-and-west direction. Each set of hourly tabulations is then treated independently and analyzed in the usual manner. When the two sets of harmonic constants have been derived the like-named constants of the north-and-south and east-and-west directions may be combined into a single resultant, which will be an ellipse, either graphically or by means of the formula

$$\tan 2\theta = \frac{H_1^2 \sin 2\kappa_1 + H_2^2 \sin 2\kappa_2}{H_1^2 \cos 2\kappa_1 + H_2^2 \cos 2\kappa_2}$$

which may be derived by writing each harmonic constant in the form $u = H_1 \cos (\theta - \kappa_1)$ for the north-and-south component and $v = H_2 \cos (\theta - \kappa_2)$ for the east-and-west component.

PREDICTION OF TIDAL CURRENTS

In tidal waters characterized by strong currents of the rectilinear type it is important for the mariner to know the time of slack water. This has led to the prediction of currents and the publication of current tables which give in advance the times of slack water for every day in the year at a number of places. Thus, the Coast and Geodetic Survey publishes annually in advance two volumes of current predictions, entitled, respectively, Current Tables, Atlantic Coast, North America, and Current Tables, Pacific Coast, North America. As now issued, the Atlantic Coast Current Tables contain the predictions of the times of slack water for each day of the year at 12 places with differences for some 500 other places. In view of the considerable diurnal inequality on the Pacific coast, the current tables for the Pacific coast give the times of slack and also the times and velocities of flood and ebb strength for each day of the year at 7 places with differences for somewhat more than 500 other places.

To predict the times of slack water, two independent methods may be used. The first, known as the nonharmonic or interval method, follows directly from the considerations developed in the section on the Relation of Time of Current to Time of Tide. In regions of little diurnal inequality very satisfactory predictions may be secured by determining the interval between current and tide and applying that interval to the predicted tides for any future time. For a station where considerable diurnal inequality exists this method is still applicable, but it is necessary to choose a port of reference the tides at which show a very nearly constant time relation to the currents at the station for which predictions are desired.

The second method of predicting rectilinear currents is by use of the tide-predicting machine, and this method is equally applicable to regions of little or of considerable inequality. The harmonic method of predicting the currents at any station implies the existence of harmonic constants for this station. These harmonic constants are derived from the hourly velocities of the current in the same manner as the harmonic constants of the tide are derived from the hourly heights of the tide. The predicting of the current by the use of the tide-predicting machine is in all respects analogous to the process as carried out for the prediction of the tides, except that in the latter case it is the times of maximum and minimum that are predicted, while for the currents it is the time of zero velocity that is usually predicted. With a predicting machine of the type used in the Coast and Geodetic Survey the prediction of currents is carried out very expeditiously.

In the case of rotary currents, since both velocity and direction of current change continually, the problem of prediction becomes quite complicated. The tide-predicting machines now in use are not adapted to the prediction of rotary currents. They may be used, however, in predicting separately the north-and-south component and the east-and-west component. The velocities of these components at stated hours of the day—say, every two hours—can thus be tabulated in adjoining columns, from which the resultant velocity and direction of the current at these times can be determined very easily by graphic means.

At the present time the most convenient method, although only approximate, consists in the use of curves such as shown in Figures 4 and 5. From a series of observations covering several months it is not a difficult matter to construct a set of curves for the current at the times of mean tides, spring tides, neap tides, tropic tides, and equatorial tides. These curves, then, give the velocity and direction of the current for each hour of the day with reference to the time of high and low water at some suitable port. The velocity and direction of the rotary tidal current at any future time may be determined with a fair degree of approximation by the use of these curves in connection with the predicted times of high and low water at the port of reference.

III. WIND-DRIVEN CURRENTS

EFFECT OF WIND

Of nontidal currents there are some, like the Gulf Stream in the Atlantic Ocean or the Kuroshiwo (Japan current) in the Pacific Ocean, which at any given point exhibit a marked uniformity in both velocity and direction of flow for considerable periods of time. Because of this uniformity it is not a difficult matter for the navigator to make allowance for the effects of such currents, since he is informed in advance of the average velocity and direction of these currents and also where they are to be encountered; but it is a difficult matter to make allowance for variable nontidal currents which change in velocity and direction in response to variations in the causes which bring them about. These variable currents are therefore of very considerable importance to the mariner, especially in coastwise navigation, since he frequently may be totally unaware of their existence.

In coastwise navigation the currents brought about by the wind are undoubtedly the most important of the variable nontidal currents. In fact, the mariner has always recognized the wind as the principal cause of nontidal currents. Of all the agencies which bring about offshore nontidal currents the wind is to the mariner the most evident and the one with the effects of which he has had most frequent experience. For many years it had been accepted by seafaring men that a wind blowing steadily over a wide stretch of water gives rise to a current which sets in the direction of the wind.

ZÖPPRITZ'S INVESTIGATION

In this opinion of a current setting with the wind the mariner received support from the mathematical investigation of the question published by K. Zöppritz[1] in 1878. From this investigation Zöppritz was led to conclude that a steadily blowing wind will, through friction, bring about a surface flow in the direction of the wind. This surface layer will, in turn, put into motion in the same direction a lower layer of water until finally (after a very considerable period of time) the whole mass of water, from top to bottom, will be flowing in the direction of the wind. He further concluded that in this moving mass of water the velocity at any point would be in inverse proportion to its depth below the surface.

The conclusions resulting from Zöppritz's analysis were accepted for a number of years, for these conclusions were in accord with the practical view of the matter and appeared also to accord with such observational material as was at hand. It is to be noted, however, that the systematic observation of currents, especially at some distance from the land, is a matter of considerable difficulty and expense, so that little observational material was at hand. It should be stated, too, in passing, that in this mathematical investigation Zöppritz did not include in his equations the effect of the earth's rotation, the assumption undoubtedly being that since the velocities of wind-driven currents were never very great the effect of the earth's rotation would be so small that it might be completely disregarded.

EKMAN'S INVESTIGATION

It was only at the beginning of the present century that attention was directed anew to the question. In correlating the drift of the ice with the wind, from the observations made during his north polar expedition, Nansen discovered that for any given period the drift of the ice was almost invariably to the right of the corresponding wind resultant, and that generally this deviation was considerable. At his instance V. W. Ekman[2] thereupon investigated the matter anew, and by introducing into the equations of motion the deflecting force of the earth's rotation and certain simplifying assumptions he arrived at the conclusion that in a large body of water of infinite depth the surface currents due to the wind set in a direc-

[1] Annalen der Physik und Chemie, Band III, 1878, pp. 582–607.

[2] The Norwegian North Polar Expedition, Scientific Results, edited by Fridtjof Nansen, London, 1902, Vol. III, p. 370 ff. See also Ekman "On the influence of the earth's rotation on ocean currents," in Arkiv för Matematik, Astronomi och Fysik, Bd. 2, No. 11, Uppsala, 1905.

tion 45° to the right of the wind in the Northern Hemisphere and 45° to the left of the wind in the Southern Hemisphere. Furthermore, the surface layer will in time put into motion a lower layer of water, but the direction of the current in this lower layer will be deflected still farther to the right (in the Northern Hemisphere), so that the deviation of the wind-driven current from the direction of the wind increases uniformly with the depth or in arithmetical progression. The velocity of the current, however, from the formula derived by Ekman decreases very rapidly with the depth—in geometrical progression, in fact—so that at a depth where the direction of the current is directly opposite to the surface current the velocity is only 4 per cent that at the surface.

It is to be noted that on the assumption of a large body of water of infinite depth the results derived by Ekman demand an abrupt change of 90° at the Equator for the surface currents due to the wind—from 45° to the right of the wind in the Northern Hemisphere to 45° to the left of the wind in the Southern Hemisphere. This abrupt change, in Ekman's words, "has, of course, no correspondence with actual reality," for the waters of the earth are not of infinite depth, and actually the angle of deflection "would begin to decrease in the neighborhood of the Equator and be zero at the Equator."[3] In fact, for an ocean of finite depth Ekman's equations show that the angle between the surface current and the wind depends on the depth. In a very shallow ocean his calculations make the angle very small—that is, the current sets nearly in the direction of the wind—but as the depth of the ocean increases the angle increases approximating to the value of 45°, being for certain depths greater than 45° and for other depths less.

It is obvious that near the coast the direction of the wind-driven current must be very considerably affected by the direction of the coast line. From his investigation Ekman found this to be the case, his calculations showing that while the surface current should still deviate to the right of the wind direction (in the Northern Hemisphere) this deviation would vary from 0 to 53°, depending on the angle between the coast line and the direction of the wind. Besides this modifying influence on the surface current he found further that the continents modify very profoundly the subsurface currents.[4]

Excepting the region in the immediate vicinity of the Equator, the results derived by Ekman show that the direction of the current due to the wind is independent of latitude. As regards the velocity of the wind-driven current, his equations show that it is not independent of the latitude, but in the open sea varies inversely as the square root of the sine of the latitude. Near the coast other factors enter in, and this simple relationship is considerably modified.

TABULATION OF LIGHT VESSEL OBSERVATIONS

In the hourly velocity and direction of the current as observed on the light vessels along the Pacific coast we have the resultant of several different kinds of currents—tidal, wind, and other. Under the circumstances it was deemed sufficient in tabulating for the current due to the wind to attempt to eliminate the effects only of the

[3] On the influence of the earth's rotation on ocean currents, p. 10.
[4] Ibid., pp. 31–32.

tidal current, for what was attainable with the observations at hand was not an exact quantitative determination of the current due to winds of given velocities and directions but rather the determination of the currents that, on the average, occur with such winds in the given localities.

It is evident that the mean value of the tidal current during a tidal period of 24 hours 50 minutes is very nearly zero Hence, if there occurred many days when the velocity and direction of the wind were constant, the effects of the tidal current would be practically eliminated by summing algebraically the velocities of the observed currents in periods of 25 hours. Unfortunately it is only at rare intervals that the wind is constant in velocity and direction for periods of 25 hours. The same result, however, may be assumed to be attained by summing over considerable periods of time the currents that occur with a given wind. This method is obviously preferable to the alternative method of eliminating the tidal current from each of the observed hourly observations or from groups covering several hours.

In deriving the current due to the wind the procedure employed consisted in tabulating the currents that occurred with winds of given direction and velocity. Since the velocity of the wind was estimated in accordance with the Beaufort scale, in which the smallest unit is about 6 miles per hour, it was found convenient to separate the winds into groups covering a range of 10 miles. A specimen sheet of the tabulation for the southeast wind at Swiftsure Bank Light Vessel is shown below.

TABLE 6.—*Currents: Wind reduction*

[Station, Swiftsure Bank Light Vessel; latitude, 48° 31′ 44″; longitude, 125° 00′ 0″; time meridian, 120 W.; wind, SE.; limits, SE. by E. to SE. by S.; directions, magnetic; year, 1919; month, January, February, March]

Wind 10-19			Wind 20-29			Wind 30-39			Wind 40-49			Wind 50-59		
Current			Current			Current			Current			Current		
Date	North	East	Date	North	East	Date	North	East	Date	North	East	Date	North	East
Jan. 10	3.8	2.5	Jan. 7	2.3	2.2	Jan. 13	4.0	2.0	Jan. 13	4.0	3.0	Jan. 14	3.5	1.1
	3.9	2.6	13	3.0	1.8		3.3	2.7		4.0	3.0		3.5	0.9
	3.6	2.6		3.1	1.8		4.8	3.5		4.2	3.1		3.9	1.7
11	3.8	2.5		2.8	1.6	14	3.8	1.9		3.7	1.5	16	3.6	3.3
	3.9	2.5		3.8	1.6		4.1	2.2		3.3	1.9		3.0	3.0
12	3.2	3.3	14	4.2	2.9		4.6	1.8	16	4.0	3.0		3.2	3.2
	3.1	3.1		4.2	3.1		4.1	2.3		4.0	3.8		------	------
	3.6	2.1	15	4.7	2.0		3.4	1.6		4.4	3.2		------	------
	3.3	1.2	21	3.8	3.2	15	4.0	2.6		2.8	1.8		------	------
15	4.0	2.0		4.4	3.2	17	4.1	2.5		3.6	1.8		------	------
17	3.8	2.1		4.1	2.5	24	4.2	2.9	25	3.4	2.4		------	------
18	4.0	2.0		4.0	3.4	25	3.2	2.6		3.3	2.0		------	------
	4.0	2.0	24	3.5	1.8		3.7	2.3	28	4.7	3.5		------	------
21	3.6	3.5		3.7	1.3		3.7	2.7	Feb. 8	3.9	2.4		------	------
24	4.0	2.3		3.5	1.4		3.5	2.3		3.5	1.9		------	------
25	3.5	1.9		3.4	1.8	27	4.0	1.6		3.3	1.7		------	------
26	4.9	1.7		3.1	1.6		4.1	2.5		3.5	1.7		------	------
27	4.3	2.4		3.8	1.6		3.9	1.6		2.5	1.4		------	------
Feb. 8	3.1	3.3		4.6	2.6		3.9	1.6		4.3	1.0		------	------
9	3.2	3.1		4.2	1.2		3.3	1.4		4.2	1.8		------	------

TABLE 6.—*Currents: Wind reduction*—Continued

Wind 10–19			Wind 20–29			Wind 30–39			Wind 40–49			Wind 50–59		
Current			Current			Current			Current			Current		
Date	North	East	Date	North	East	Date	North	East	Date	North	East	Date	North	East
Feb. 9	4.2	3.2	Jan. 24	4.4	1.5	Jan. 27	4.4	2.2	Feb. 8	4.2	2.9		------	------
	3.5	3.9		4.6	2.7		4.3	1.7		4.1	2.5		------	------
	3.1	3.8		4.3	2.0		4.1	2.5		3.8	2.3		------	------
	2.7	3.5		4.3	2.0		4.0	3.1	16	3.2	2.2		------	------
10	3.2	2.7		4.4	2.7		3.8	3.0	Mar. 17	4.3	2.4		------	------
	2.7	2.7	25	3.7	2.1		3.8	3.0	30	3.8	2.9		------	------
	2.8	2.4		3.4	2.1		4.9	3.0		4.3	2.4		------	------
	2.7	1.8		3.3	2.0	Feb. 12	4.2	2.9		3.6	2.7		------	------
	3.2	2.0		3.2	2.4	Mar. 4	4.4	1.8		------	------		------	------
	4.3	2.4		3.0	2.8	17	4.5	2.2		------	------		------	------
	3.5	1.6		3.4	2.6	30	4.4	2.8		------	------		------	------
	4.4	2.8	27	3.9	2.6		4.3	2.8		------	------		------	------
12	3.3	3.8		4.4	2.4		3.6	2.7		------	------		------	------
	3.5	3.6		4.1	2.2		2.8	2.6		------	------		------	------
	3.8	3.2	Feb. 3	3.5	1.6		------	------		------	------		------	------
	3.8	2.9	8	3.2	2.9		------	------		------	------		------	------
13	3.8	3.3		3.2	3.1		------	------		------	------		------	------
	3.5	3.6		3.2	3.1		------	------		------	------		------	------
	3.2	3.4	Mar. 1	4.2	3.2		------	------		------	------		------	------
	3.1	2.8	4	4.5	2.7		------	------		------	------		------	------
Sum	142.9	108.1		150.4	91.3		135.2	80.9		105.9	66.2		20.7	13.2
Divisor	40	40		40	40		34	34		28	28		6	6

In the tabulation above the observed hourly currents have been resolved into magnetic north-and-south and east-and-west directions and three added to the resolved values to do away with the necessity of dealing with both positive and negative numbers in the same column. This resolution, as explained before, is very expeditiously carried out graphically. In fact, the resolutions are made once for all in a column of the record book shown on page 3. The resolved values are then used in the tabulations for deriving both the wind current and the tidal current. After tabulating the currents, as shown on the specimen page, for a year the page sums for the various winds are collected, summed, and a mean derived. The resultant current for each wind-velocity group is then easily determined in velocity and direction, preferably from a graphic table.

It is to be noted that the energy of the wind is transmitted to the water in two different ways. There is, first, the direct effect of the wind on the water produced by friction of the moving air on the surface of the water; and, secondly, there is the effect of the impact of the wind on the waves. In the observations on the currents made on the light vessels no attempt is made to distinguish between the two, the resultant current due to both the friction and impact of the wind being considered the current due to the wind.

IV. OBSERVATIONS ON SAN FRANCISCO LIGHT VESSEL

LOCATION AND LENGTH OF SERIES

San Francisco Light Vessel is stationed in latitude 37° 45′ 03″ N., longitude 122° 41′ 30″ W., in 18 fathoms of water, about 9 miles from the coast and about 10 miles southwesterly from the entrance to San Francisco Bay. The location of the vessel is shown in Figure 10.

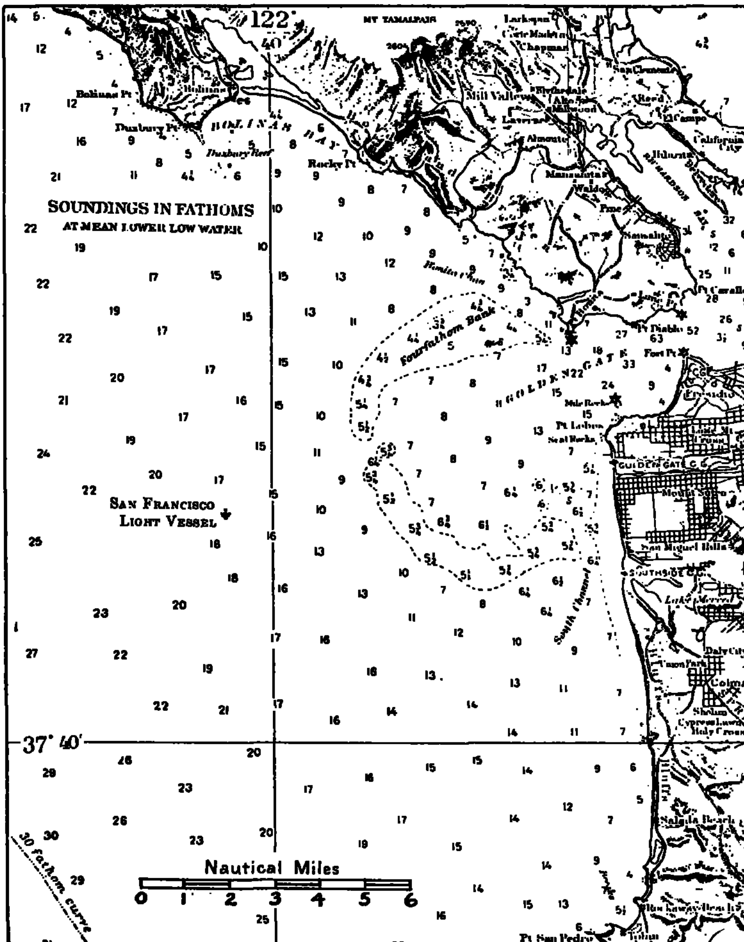

FIG. 10.—Location of San Francisco Light Vessel

The current observations on this light vessel consist of two series of hourly observations, the first one extending from January 23, 1915, to June 30, 1916, and the second extending from September 1, 1918, to December 31, 1920. In the 1915–16 series the observations were made with a log line graduated for a 28-second run, which interval was determined by use of a sand glass. In the 1918 to 1920 series the observations to March 1, 1920, were likewise made with a 28-second sand glass, but after that date the observations were carried on with a log line graduated for a run of 60 seconds, the interval being determined by use of a stop watch.

TIDAL CURRENT

The tidal current at San Francisco Light Vessel is of the rotary type; that is, the direction of the current changes continually. To determine the velocity and direction of such a current, it is most convenient to tabulate the observed hourly velocity and direction of the current with reference to the times of high and low water at some suitable port. For the observations on San Francisco Light Vessel the predicted times of high and low water for San Francisco (Fort Point), as appearing in the tide tables issued by this Survey, were used.

An approximate mean value for the velocity and direction of the current may be obtained by the tabulation of the observations, as shown on page 2, but it is necessary in the case of the observations on the Pacific coast light vessels to use resolved values of the current—that is, the hourly velocity and direction of the current must be resolved into two directions perpendicular to each other. And because of the very considerable diurnal inequality in the currents on the Pacific coast it is necessary to tabulate not only with reference to high and low water but also to distinguish between the higher high and lower high waters of a day and between the lower low and higher low waters.

The results derived from a tabulation as outlined above give the tidal current as modified by the wind current or other nontidal current. To eliminate these nontidal currents, advantage is taken of the fact that the mean value of the tidal current as resolved is approximately zero if not modified by nontidal currents. If, therefore, we sum separately the north-and-south and the east-and-west components over a period of 29 days, the final result will be the resultant nontidal current for that period. Upon plotting the hourly values of the current as derived from a tabulation with reference to the times of high and low water, and also plotting the resultant value of the nontidal current for the same period, it is a simple matter to derive the tidal current freed from the effects of nontidal currents. The following example will make this clear.

The tabulation of the observations made on San Francisco Light Vessel during the month of February, 1916, gave the results shown diagrammatically in Figure 11. In this figure *HH* and *LL* refer, respectively, to the times of higher high and lower low water at San Francisco (Fort Point), while *H* and *L* refer to the times of lower high and higher low water, respectively, the numbers following these symbols indicating the number of hours before or after the respective tides, a minus sign denoting before and a plus sign after. Each line from the origin gives by its length the average velocity of the current during the month for its particular hour of tide and by its direction the average direction of the current for that hour, but when the north-and-south and east-and-west components of the hourly values of the current for the month are summed it is found that the average value of the north-and-south component is 0.02 knot northerly (magnetic) while that of the east-and-west component is 0.54 westerly (magnetic). This means that the nontidal current for the month in question had a velocity of 0.54 knot in a direction N. 88° W. magnetic, or N. 70° W. true. Plotting this position as point *C* in Figure 11, this becomes the origin from which the hourly values of the tidal current freed from the effects of the nontidal current are to be measured, the lines joining *C* with each of the points *H*, *L*, etc., giving the velocity and direction of the tidal current for each of those hours.

The dashed-line curve was drawn to fit approximately the ends of the radii vectores, and it is to be noted that it defines two somewhat irregular ellipses, the larger one having a period of about 14 hours and the smaller one a period of about 11 hours. The smaller ellipse

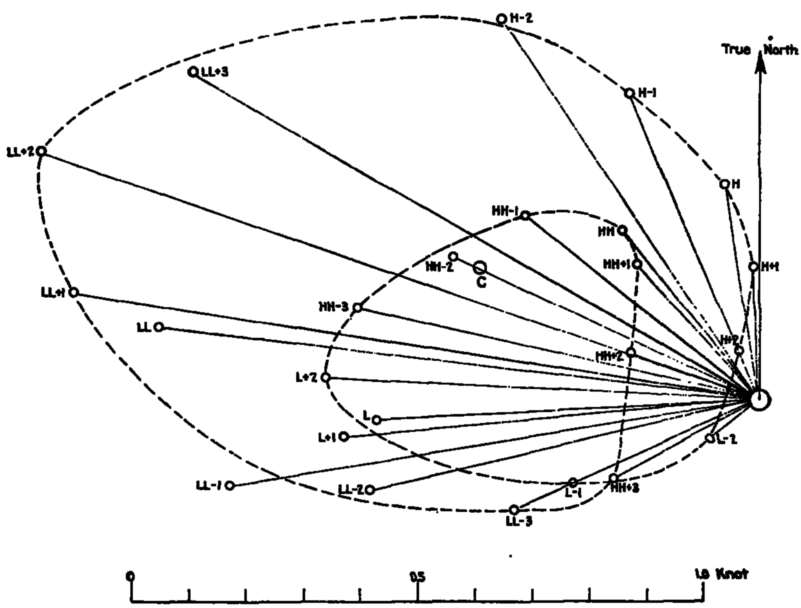

FIG. 11.—Current curve, San Francisco Light Vessel, February, 1916

is associated with higher high and higher low water at San Francisco, while the larger ellipse is associated with lower low and lower high water at San Francisco.

Table 7 gives, with reference to the time of tide at San Francisco, the velocity and direction of the tidal current for each tidal hour as determined from 29-day groups for the months of February, May, August, and November. For 1916, however, the values given were derived from the observations for February and May only. In this table the effects of the nontidal current have been eliminated as explained above. For each month the 29-day group begins on the 1st and ends on the 29th; for February, however, the last day of January is included when necessary to complete the 29-day group. The velocities are given in knots and the directions are true, not magnetic, and are reckoned clockwise from north as zero. Here, too, *HH* stands for the time of higher high water at San Francisco (Fort Point), *LL* for the time of lower low water, *H* for the time of lower high water, and *L* for the time of higher low water, while the figures following these letters give the number of hours before or after the time of the particular tide. The means for each year in this table are not the arithmetical means of the monthly velocities and the directions. They were determined by resolving the monthly means into north-and-south and east-and-west directions and summing algebraically, which procedure was likewise employed for determining the final mean given in the last column. In this final mean, however, it was thought best to use only the values for the years 1915, 1919, and 1920, since for 1916 there were at hand the results for only two months.

TABLE 7.—*Mean tidal current, San Francisco Light Vessel*

[Referred to time of tide at San Francisco]

Tidal hour	1915		1916		1919		1920		Mean[1]	
	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.
	Knots	*Deg.*	*Knots*	*Deg.*	*Knots*	*Deg.*	*Knots*	*Deg.*	*Knots*	*Deg.*
HH−3	0.10	96	0.10	217	0.04	63	0.10	90	0.08	76
HH−2	.13	86	.02	63	.06	72	.11	80	.10	79
HH−1	.12	85	.11	41	.06	81	.07	64	.08	76
HH	.14	98	.20	82	.07	82	.06	90	.09	96
HH+1	.16	128	.22	95	.04	117	.04	135	.09	126
HH+2	.19	162	.23	121	.13	157	.10	180	.14	163
HH+3	.27	167	.30	143	.18	164	.18	192	.20	174
LL−3	.28	178	.33	168	.20	171	.20	200	.22	183
LL−2	.31	187	.35	196	.25	173	.21	203	.25	187
LL−1	.28	219	.49	135	.25	209	.19	208	.24	213
LL	.38	253	.54	222	.27	236	.18	232	.27	243
LL+1	.55	279	.69	280	.32	277	.20	276	.36	278
LL+2	.63	301	.79	293	.40	297	.26	306	.43	301
LL+3	.58	324	.69	311	.42	325	.28	322	.42	324
H−2	.37	3	.50	5	.33	2	.26	358	.32	0
H−1	.34	17	.45	32	.31	13	.25	5	.30	12
H	.26	43	.41	60	.23	31	.22	18	.23	31
H+1	.20	63	.43	75	.19	51	.17	24	.18	45
H+2	.21	95	.40	98	.14	82	.09	64	.14	82
L−2	.25	108	.41	116	.17	111	.09	122	.17	110
L−1	.30	127	.37	140	.22	141	.14	135	.22	133
L	.29	139	.26	176	.21	149	.18	146	.22	144
L+1	.24	144	.26	184	.15	157	.18	142	.19	148
L+2	.17	159	.16	207	.10	163	.13	138	.13	153

[1] Mean of 1915, 1919, and 1920.

The values of the velocity and direction in Table 7 for the same tidal hour are seen in some cases to differ considerably in the different years. Thus, for three hours before higher high water the direction in the 1916 column differs by more than 100° from the value in 1915, but it will be noted that the velocity of the current for that tidal hour is small, and that for the larger velocities the agreement is very much closer. For example, for the current one hour after lower low water the greatest difference in direction for the four years given is but four degrees. In general, it may be said that in view of the small velocity of the current at San Francisco Light Vessel and in further view of the methods of observation and tabulation employed the agreement shown in Table 7 is as close as could be expected.

The mean current curve for San Francisco Light Vessel is shown in Figure 12, in which *c* is the origin of coordinates. The current is seen to exhibit very considerable diurnal inequality. The larger ellipse which is associated with the lower low water and lower high water at San Francisco has a period of about 18 hours, while the smaller ellipse which is associated with higher high water and higher low water at San Francisco has a period of about 7 hours.

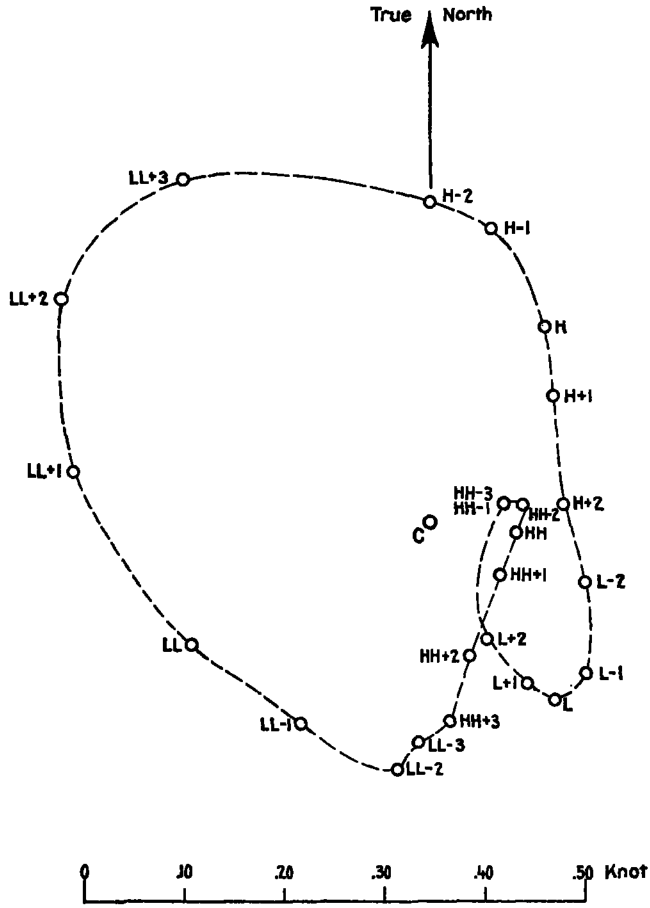

FIG. 12.—Mean tidal current curve, San Francisco Light Vessel

Since Figure 12, which represents the mean tidal current at San Francisco Light Vessel, exhibits considerable diurnal inequality, it follows that this feature of the current must show very marked changes in response to changes in the moon's declination. Figure 13 represents diagrammatically the current at San Francisco Light Vessel at the time the moon's declination is very small; that is, when the moon is on or close to the Equator. The current at such times is called the equatorial current, or the minimum diurnal current.

From observations it is known that the diurnal inequality, both in tides and currents, is greatest not on the day when the moon has its maximum declination but generally about a day later. This lag is known as the "age of the diurnal inequality" or "diurnal age." The diurnal age can be determined directly from observations, although a long series is required to do this. It may also be determined from the harmonic constants, the formula being age in

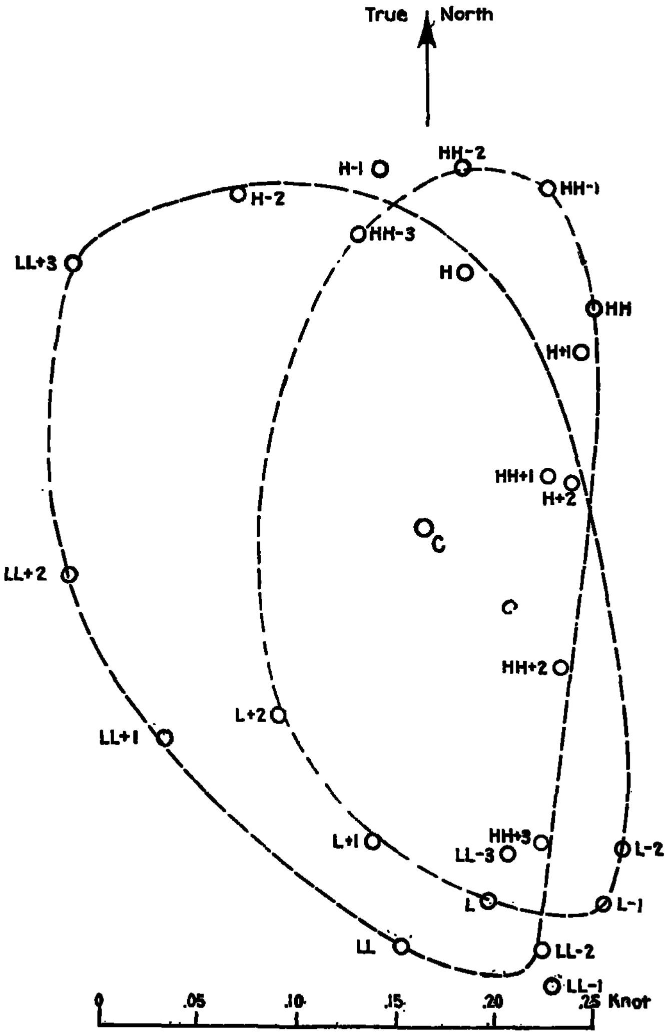

FIG. 13.—Equatorial tidal current curve, San Francisco Light Vessel

hours=0.911 ($K_1°-O_1°$). The diurnal age is also the interval elapsing between the moon's equatorial passage and the occurrence of the equatorial tides or currents. The diurnal age of the tide at San Francisco is about 16 hours; hence, in deriving the equatorial current represented in Figure 13 the diurnal age was taken as one day.

Furthermore, in order to have the benefit of a considerable number of observations, groups of three days were used, the currents on the day of the moon's equatorial passage and the two days following being used. This procedure has the further advantage of minimizing accidental errors and the effects of unusual or transitory conditions, meteorological or other. In deriving Figure 13 the observations throughout the years 1915, 1919, and 1920 were used.

It is to be noted that the current curve shown in Figure 13 represents the tidal current alone, the nontidal current for the days of observations used having been eliminated, as explained previously

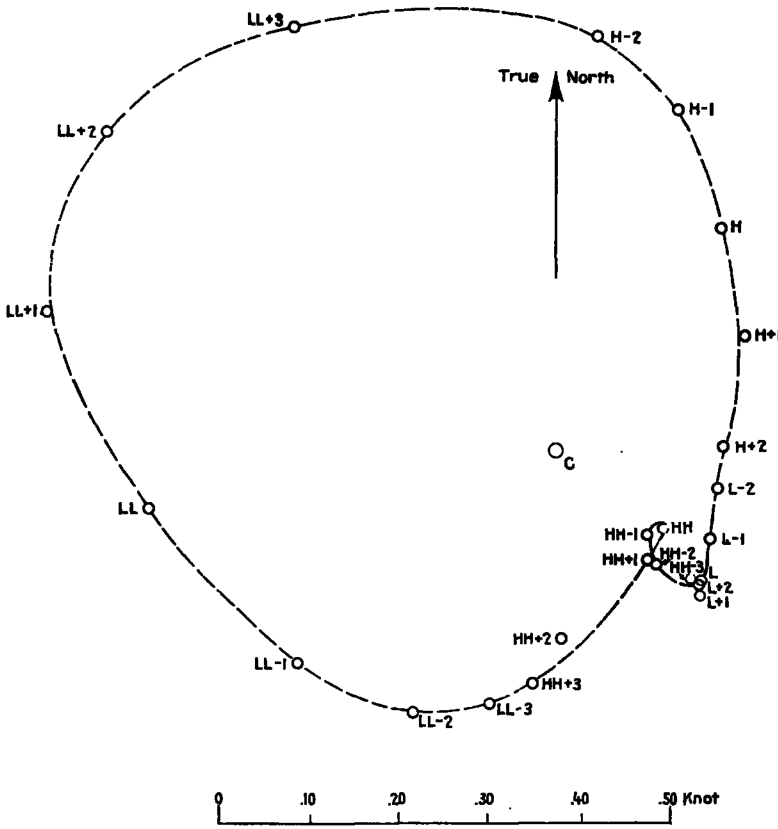

FIG. 14.—Tropic tidal current curve, San Francisco Light Vessel

in connection with the derivation of the mean tidal current. The two current ellipses are seen to be much alike, and, hence, on days when the moon's declination is close to zero there is little diurnal inequality in the current at San Francisco Light Vessel. On comparing Figure 13 with Figure 12, which is the mean current curve and may, therefore, be taken to represent the current halfway between the equatorial and tropic currents, it is seen that the current changes considerably in the seven days from the moon's equatorial passage to its attainment of half its semimonthly maximum declination.

In view of the marked change in the current shown in Figures 12 and 13, it is to be expected that the diurnal inequality in the current at San Francisco Light Vessel at the times when the moon attains its semimonthly maximum declination would be very considerable. This is borne out by the observations as shown in Figure 14, which represents the current curve at the time when the moon is at its semimonthly maximum declination. Since the moon is then near one of the tropics, the current at such times is called the tropic current.

As in the case of the equatorial current, three-day groups were used in deriving the tropic current, these days being the day of the moon's maximum semimonthly declination and the two days following. This amounts to taking the diurnal age of the current as one day. The nontidal current was eliminated, as explained for the equatorial current, and here, too, the observations throughout the years 1915, 1919, and 1920 were used.

At the times of tropic current the current at San Francisco Light Vessel becomes very nearly diurnal, the smaller ellipse practically vanishing. The greatest velocity of the current comes about two hours after the time of lower low water at San Francisco and sets northwesterly with a velocity of about 0.6 knot. At the times of equatorial current the strength of the current is barely a quarter of a knot, or about half of the tropic current.

NONTIDAL CURRENT

The nontidal current was determined by summing algebraically the observed hourly values of the current after they had been resolved into north-and-south and east-and-west components and deriving the mean. This was done in groups of 29 days for each month, and the resultant velocity and direction of the nontidal current is shown in Table 8. The velocities are given in knots and the directions are true, not magnetic, and are reckoned clockwise from north as zero. For each month the first 29 days were used, except for the month of February, for which the last day of January was included when necessary to make a 29-day group.

TABLE 8.—*Nontidal current, San Francisco Light Vessel; average velocity and direction*

Month	1915		1916		1918		1919		1920	
	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.
	Knots	*Deg.*	*Knots*	*Deg.*	*Knots*	*Deg.*	*Knots*	*Deg.*	*Knots*	*Deg.*
January	-------	-------	0.44	313	-------	-------	0.32	318	0.12	293
February	0.50	310	.54	290	-------	-------	.11	310	.08	318
March	.28	296	.20	285	-------	-------	.14	296	.02	224
April	.08	248	.15	260	-------	-------	.10	289	.05	145
May	.27	301	.12	229	-------	-------	.17	312	.08	138
June	.12	229	.07	288	-------	-------	.04	315	.14	348
July	.15	316	-------	-------	-------	-------	.13	336	.04	344
August	.10	341	-------	-------	-------	-------	.02	171	.09	352
September	.06	360	-------	-------	0.05	176	.04	189	.09	135
October	.06	347	-------	-------	.03	18	.05	18	.03	108
November	.15	2	-------	-------	.14	324	.01	243	.17	308
December	.18	331	-------	-------	.16	302	.18	300	.28	290
Mean	.15	311	.23	288	.06	306	.10	312	.05	310

The observations having been made with a 15-foot pole floating 1 foot out of water, the data of Table 8 may be taken to pertain to the current at a depth of 7 feet below the surface. At this depth the nontidal current is seen to have set southwesterly or northwesterly the greater part of the time. The greatest average monthly velocity occurs during the winter months, the current setting northwesterly. During these months the direction of the prevailing wind is northwesterly, and hence in a direction opposite that of the nontidal current. It follows, therefore, that the nontidal current at San Francisco Light Vessel is not due to the local wind.

The precipitation in California is greatest during the winter months. Hence, it is during these months that the discharge of drainage waters through the Golden Gate is a maximum. The ebb current, which carries the drainage waters out to sea, sets S. 45° W. through the Golden Gate, while the light vessel is stationed about 11 nautical miles S. 70° W. from Golden Gate entrance. The light vessel thus lies somewhat to the north of the direction taken by the ebb current on its emergence from Golden Gate, but the deflecting force of the earth's rotation acts to deflect the current coming from the Golden Gate to the right or northward, and thus in the direction of the light vessel. It would, therefore, appear that the drainage waters from San Francisco Bay constitute a factor in the nontidal current at San Francisco Light Vessel.

The means for the different years in Table 8 were derived from the resolutions of the hourly velocity and direction of the current for the months shown for each year and may differ slightly from the mean of the monthly values in Table 8. For each year the average direction of the nontidal current is northwesterly, the velocity being approximately 0.1 knot. The velocity for 1916, which stands out with a relatively large value, is undoubtedly due to the fact that this value is based on the data for the winter and spring months, during which the greater part of the rainfall of the year takes place. For the period of observations covered by Table 8 the velocity of the nontidal current averaged 0.11 knot, the direction being 304°.

WIND CURRENT

The current due to the wind at San Francisco Light Vessel was derived as explained in Section III under "Tabulation of light vessel observations." Tabulations of the resolved velocities of the current were made for 16 directions of the wind, each direction thus covering a range of two points of the compass, or 22½°. The results of this tabulation are shown in Table 9, in which the velocity of the wind is given in miles per hour, the velocity of the current in knots, the directions being true and not magnetic.

TABLE 9.—*Wind currents, San Francisco Light Vessel*

Wind from—	Year	Wind 10–19			Wind 20–29			Wind 30–39			Wind 40–49			Wind 50–59		
		Current			Current			Current			Current			Current		
		No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.
			Knots	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*
N	1915	18	0.47	278	8	0.37	226	2	0.81	148						
	1916	11	.52	294												
	1918	22	.25	153												
	1919	13	.38	277	13	.40	174	4	.44	172						
	1920	25	.12	288	24	.27	196									
Mean		89	.21	270	45	.31	194	6	.54	162						
NNE	1915	2	.46	227												
	1916	4	.36	186												
	1918	17	.21	247	5	.61	196				1	0.50	223			
	1919	15	.35	259	8	.54	206	3	.30	196						
	1920	15	.21	278	23	.19	252	3	.40	226						
Mean		53	.24	252	36	.29	220	6	.33	214	1	.50	223			
NE	1915	11	.16	357	5	.27	265									
	1916	4	.46	153												
	1918	16	.18	278	7	.54	236									
	1919	38	.22	268	15	.46	262									
	1920	14	.27	251	26	.22	221	2	.63	218						
Mean		83	.17	266	53	.32	243	2	.63	218						
ENE	1915	104	.44	295	8	.40	332									
	1916	57	.61	279	12	.74	291				1	1.90	292			
	1918	121	.22	278	37	.27	279									
	1919	185	.31	292	113	.29	271									
	1920	125	.30	297	45	.35	268	5	.31	238						
Mean		592	.34	290	215	.32	276	5	.31	238	1	1.90	292			
E	1915	83	.47	298	19	.32	324									
	1916	42	.82	313	7	1.09	279	3	1.76	273						
	1918	62	.44	317	11	.29	294									
	1919	187	.36	303	36	.29	292									
	1920	199	.36	300	27	.58	292									
Mean		573	.42	304	100	.42	294	3	1.76	273						
ESE	1915	48	.48	330	20	1.08	327	2	1.15	322						
	1916	36	.90	294	4	.80	336									
	1918	3	.38	324	4	.46	336									
	1919	126	.29	323	9	.25	318									
	1920	133	.31	294	13	.45	300									
Mean		346	.37	308	50	.68	323	2	1.15	322						
SE	1915	74	.56	326	46	.56	342	9	.78	348	21	.60	347	3	0.75	356
	1916	10	.50	307	2	.30	380									
	1918	9	.16	336	6	.29	365	8	.40	330	9	.66	335			
	1919	131	.29	339	28	.48	354	6	.70	347						
	1920	126	.29	316	98	.34	315	45	.52	314	14	.75	327	3	.65	334
Mean		350	.34	326	180	.40	333	68	.54	325	44	.65	337	6	.69	346
SSE	1915	206	.42	352	95	.69	354	53	.58	358	53	.84	347	13	1.27	340
	1916	94	.47	318	49	.54	343	14	.84	333						
	1918	15	.29	362	10	.38	380	4	.59	370	1	.41	368			
	1919	132	.36	340	60	.40	344	26	.59	342	8	.87	343	4	.58	339
	1920	84	.32	327	75	.54	327	10	.74	335	7	.48	342			
Mean		531	.38	339	289	.54	344	107	.62	347	69	.80	346	17	1.11	340
S	1915	209	.48	342	34	.65	340	5	.69	347	1	.61	385	1	1.44	364
	1916	129	.52	324	61	.62	358	29	.45	347	16	.91	332	11	.83	341
	1918	35	.14	355	11	.52	341	2	.39	326	2	.26	365			
	1919	208	.27	342	55	.56	356	21	.51	380	28	.52	353	1	.64	325
	1920	199	.34	350	33	.42	343	3	.69	353	4	.55	333			
Mean		780	.37	340	194	.56	351	60	.48	359	51	.62	343	13	.85	343

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TABLE 9.—*Wind currents, San Francisco Light Vessel*—Continued

Wind from—	Year	Wind 10-19			Wind 20-29			Wind 30-39			Wind 40-49			Wind 50-59		
		Current			Current			Current			Current			Current		
		No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.
			Knots	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*
SSW	1915	177	0.39	328	9	0.49	326	4	0.72	350	2	1.51	364	1	1.12	358
	1916	105	.54	338	25	.63	359	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1918	9	.40	345	-----	-----	-----	-----	-----	-----	1	.36	424	-----	-----	-----
	1919	151	.35	316	15	.42	327	11	.42	364	1	.54	346	-----	-----	-----
	1920	123	.22	336	21	.43	368	-----	-----	-----	-----	-----	-----	-----	-----	-----
Mean	------	565	.37	329	70	.49	348	15	.50	359	4	.93	6	1	1.12	358
SW	1915	177	.39	350	9	.49	348	4	.72	372	2	1.51	26	1	1.12	20
	1916	34	.47	349	20	.34	387	1	.10	297	-----	-----	-----	-----	-----	-----
	1918	9	.40	367	-----	-----	-----	-----	-----	-----	1	.36	86	-----	-----	-----
	1919	151	.35	338	15	.42	350	11	.42	386	1	.54	8	-----	-----	-----
	1920	123	.22	358	21	.43	390	-----	-----	-----	-----	-----	-----	-----	-----	-----
Mean	------	494	.34	348	65	.38	13	16	.47	20	4	.93	28	1	1.12	20
WSW	1915	124	.34	331	7	.16	73	2	.21	336	7	.26	47	3	.72	43
	1916	53	.39	317	16	.29	24	6	.21	400	5	.88	110	-----	-----	-----
	1918	24	.14	336	8	.30	90	2	.52	364	-----	-----	-----	-----	-----	-----
	1919	321	.25	332	35	.13	−6	9	.29	365	1	1.08	−1	-----	-----	-----
	1920	236	.20	355	38	.27	9	4	.44	141	5	.60	178	-----	-----	-----
Mean	------	758	.25	336	104	.19	18	23	.18	30	18	.33	111	3	.72	43
W	1915	209	.09	335	21	.16	264	4	.25	61	-----	-----	-----	-----	-----	-----
	1916	56	.22	314	6	.02	298	4	.10	17	-----	-----	-----	-----	-----	-----
	1918	25	.06	484	11	.10	213	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1919	293	.06	346	79	.18	182	8	.41	90	2	.30	107	-----	-----	-----
	1920	141	.17	360	19	.21	70	-----	-----	-----	-----	-----	-----	-----	-----	-----
Mean	------	724	.09	343	136	.10	183	16	.27	79	2	.30	107	-----	-----	-----
WNW	1915	727	.04	251	176	.38	178	13	.17	202	1	1.00	158	-----	-----	-----
	1916	369	.13	253	151	.25	202	56	.24	183	7	.48	145	-----	-----	-----
	1918	204	.18	171	37	.28	146	3	.42	150	3	.47	199	-----	-----	-----
	1919	992	.06	333	612	.10	179	52	.38	162	7	.16	116	-----	-----	-----
	1920	1,077	.03	151	856	.18	158	78	.29	147	22	.21	150	-----	-----	-----
Mean	------	3,369	.03	661	,832	.17	170	202	.28	162	40	.28	155	-----	-----	-----
NW	1915	1,521	.10	232	831	.28	178	68	.72	157	43	1.12	138	17	1.30	146
	1916	372	.23	231	327	.27	209	116	.39	180	40	.72	144	2	.50	147
	1918	291	.07	179	64	.30	179	6	.29	136	1	.42	150	-----	-----	-----
	1919	781	.05	268	703	.21	169	203	.34	163	36	.42	142	3	.63	189
	1920	537	.04	231	460	.18	153	136	.37	137	102	.62	135	-----	-----	-----
Mean	------	3,502	.09	2332	,385	.23	177	529	.39	159	222	.70	138	22	1.11	149
NNW	1915	177	.25	294	82	.25	222	31	.63	191	-----	-----	-----	-----	-----	-----
	1916	174	.43	269	80	.42	233	22	.36	174	28	.49	177	9	.39	105
	1918	148	.07	227	60	.28	166	8	.69	157	11	.23	175	5	.28	223
	1919	318	.16	294	145	.14	209	27	.35	208	3	.84	147	-----	-----	-----
	1920	335	.10	243	191	.18	190	47	.36	171	19	.44	120	-----	-----	-----
Mean	------	1,152	.17	274	558	.21	207	135	.42	183	61	.40	157	14	.22	128

It is to be noted that the directions of the wind as recorded by the observers on the light vessel were given with reference to the ship's compass. These directions, therefore, involved not only the variation of the compass but also its deviation. For the purpose in hand it was deemed advisable to tabulate with reference to the wind directions as observed and to correct the yearly means for deviation on the assumption that the ship headed in the direction of the wind. This procedure reduced the labor of tabulation materially.

The correction for variation likewise was applied to the yearly means. The resulting wind directions were, therefore, not for the cardinal and intercardinal points. However, the advantages of giving the table for the cardinal and intercardinal points are so obvious that the directions of the wind as derived after applying the corrections for deviation and variation were further corrected to the nearest direction shown in Table 9 by adding or subtracting the required number of degrees from both wind and current. This procedure made it necessary to use the same set of data for both the south-southwest and southwest directions, except for the year 1916.

It will be more convenient to designate the winds in the various columns of Table 9 by one velocity rather than by the two limiting velocities. Thus, winds of 10 to 19 miles per hour will be spoken of as winds of 15 miles per hour, winds of 20 to 29 miles as 25-mile winds, etc. In general, it is seen that the mean velocities of the current for the various wind directions in Table 9 show an increase with increased wind velocity, as was to be expected. It will be recalled that for the south-southwest and southwest winds very nearly the same set of data was used. Hence, in deriving a mean velocity of the current due to winds of various velocities, it will be necessary to omit either the results for the south-southwest or southwest winds. Omitting the southwest winds the average velocity of the wind current at San Francisco Light Vessel, as derived directly from the mean values of Table 9, is 0.26 knot for a 15-mile wind, 0.35 knot for a 25-mile wind, 0.56 knot for a 35-mile wind, 0.67 knot for a 45-mile wind, and 0.83 knot for a 55-mile wind.

The average velocities of the current for the 15 and 25 mile winds, as derived in the preceding paragraph, may be taken as approximately correct, since these results are based on numerous observations in each case. For the 35, 45, and 55 mile winds, however, it is to be noted that some of the data used depend on but few observations, and the currents associated with these data stand out strikingly different from the results based on a greater number of observations, as, for example, the current for the 35-mile wind from the east. It would appear of advantage, therefore, to omit from the data used for deriving the average current for winds of different velocities all results based on less than 10 observations. This procedure gives for the 35-mile wind a current of 0.41 knot; for the 45-mile, 0.54 knot; and for the 55-mile wind, 0.82 knot. In general, therefore, the velocity of the wind-driven current at San Francisco Light Vessel is about 1½ per cent of that of the wind.

It is to be noted, however, that the velocity of the current varies not only with the velocity of the wind but also with the direction of the wind. While the average current is 0.26 knot for a 15-mile wind, Table 9 shows that a 15-mile wind from the east is accompanied by a current with a velocity of 0.42 knot, while a wind of the same strength from the west-northwest is accompanied by a current with a velocity of 0.03 knot. In the one case the current has a velocity of 3.2 per cent that of the wind, while in the other case the velocity of the current is but 0.2 per cent that of the wind. Both cases exhibit a relatively wide divergence from the 1½ per cent derived as the average relation of current velocity to wind velocity.

It will be recalled that for the period of observations covered by Table 9 the nontidal current at San Francisco Light Vessel had an average velocity of 0.11 knot setting 304°. If it be assumed, as a first approximation, that this nontidal current was entirely free from any resultant wind currents, it follows that the wind currents of Table 9 are actually the resultants of the true wind current and the nontidal current. Graphically, the average nontidal current may be easily removed from the mean currents of the various wind directions, the resulting values being shown in Table 10.

TABLE 10.—*Wind currents, San Francisco Light Vessel, freed from average nontidal current*

Wind from—	Wind 10–19			Wind 20–29			Wind 30–39			Wind 40–49			Wind 50–59		
	Current			Current			Current			Current			Current		
	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.
		Knots	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*
N	89	0.13	243	45	0.36	178	6	0.63	156	-----	-----	-----	-----	-----	-----
NNE	53	.19	226	36	.30	199	6	.35	194	1	0.50	211	-----	-----	-----
NE	83	.11	227	53	.28	224	2	.63	208	-----	-----	-----	-----	-----	-----
ENE	592	.24	284	215	.23	263	5	.28	218	1	1.80	293	-----	-----	-----
E	573	.31	304	100	.31	290	3	1.65	271	-----	-----	-----	-----	-----	-----
ESE	346	.26	310	50	.58	326	2	1.04	324	-----	-----	-----	-----	-----	-----
SE	350	.24	336	180	.31	343	68	.44	328	44	.56	343	6	0.61	353
SSE	531	.30	351	289	.46	353	107	.54	355	69	.72	352	17	1.02	344
S	780	.29	353	194	.49	360	60	.43	11	51	.54	350	13	.77	348
SSW	565	.28	339	70	.42	358	15	.45	11	4	.88	12	1	1.06	3
SW	494	.27	4	65	.36	29	16	.45	33	4	.92	35	1	1.10	26
WSW	758	.17	356	104	.19	51	23	.20	62	18	.43	114	3	.74	51
W	724	.07	68	136	.18	152	16	.35	91	2	.40	111	-----	-----	-----
WNW	3,369	.13	112	1,832	.25	152	202	.37	152	40	.38	146	-----	-----	-----
NW	3,502	.12	171	2,385	.31	161	529	.48	152	222	.81	136	22	1.22	136
NNW	1,152	.09	238	558	.25	181	135	.49	172	61	.49	150	14	.33	126

It is evident that the results of Table 10, which are derived by subtracting the average nontidal current from the results of Table 9, can give but a first approximation to the true wind current, for that procedure implies that the nontidal current has a constant velocity throughout the year, which Table 8 shows to be not the case. Nevertheless, the results of Table 10 are more concordant than are those of Table 9. For example, the velocities of the current brought about by the 15-mile wind show less extreme values, the current for the east wind being now reduced by 0.11 knot and the current for the west-northwest wind increased by 0.10 knot. The average velocities of the current with winds of different velocities, however, are not changed much. Omitting the data for the southwest wind and the data based on less than 10 observations, Table 10 gives for the 15-mile wind an average current velocity of 0.20 knot; for the 25-mile, 0.33 knot; 35-mile wind, 0.42 knot; 45-mile wind, 0.56 knot; 55-mile wind, 0.84 knot.

The direct results of the tabulation in Table 9 show that the direction of the wind current at San Francisco Light Vessel is generally to the right of the wind, except with winds from the southwest quadrant. An average of the mean values of the direction of the current for the different directions of the wind gives for the 15-mile wind a deviation to the right of 50° with winds from the northeast quadrant, 10° to the right with winds from the southeast quadrant, 70° to the left with winds from the southwest quadrant (omitting the southwest winds), and 40° to the right with winds from the northwest quadrant.

In part, the deviation of the current to the left with winds from the southwest quadrant is obviously to be ascribed to the effect of the nontidal current. Thus, Table 9 shows that for the different strengths of the wind from the southwest quadrant the deviation to the left becomes less as the velocity of the wind increases, and in Table 10, in which the wind current is freed from the effect of the average nontidal current, it is seen that the deviation of the current to the left with winds from the southwest quadrant is considerably less than in Table 9.

From Table 10, omitting the data for southwest winds, since these very nearly duplicate the data for the south-southwest winds, the average deviation of the current from the direction of the wind is 12° to the right with 15-mile winds, 14° to the right with 25-mile winds, and 4° to the right with 35-mile winds. For the 45 and 55 mile winds the data is not sufficient to determine the average deviation, but the indications are that this deviation is to the right.

V. OBSERVATIONS ON BLUNTS REEF LIGHT VESSEL

LOCATION AND LENGTH OF SERIES

Blunts Reef Light Vessel is stationed off the coast of northern California, in latitude 40° 26′ 04″ N. and longitude 124° 30′ 14″ W. It is anchored in 28 fathoms of water about 3½ miles from Cape Mendocino. The location of the vessel is shown in Figure 15.

For Blunts Reef Light Vessel there are at hand the results for three series of observations. The first series begins on January 17, 1915, and ends April 16, 1915. The second series begins August 1, 1915, and ends June 30, 1916. The last series covers the period from July 25, 1918, to December 31, 1920. In all, the observations cover a period of 43 months. For the first 34 months the observations were made with a log line graduated for an interval of 28 seconds, this interval being determined by a sand glass. For the last 9 months, beginning with April, 1920, the observations were carried on with a stop watch and a log line graduated for a 60-second run.

TIDAL CURRENT

The tidal current at Blunts Reef Light Vessel is weak, having at strength a velocity of about 0.1 knot. This tidal current is therefore masked by the nontidal current. In Table 11 are given the hourly values of the tidal current at the light vessel with reference to the time of tide at Humboldt Bay, Calif., which lies about 22 nautical miles northeastward of the light vessel. The predicted times of the high and low waters at Humboldt Bay are given for every day of the year in the tide tables published annually by the Coast and Geodetic Survey.

The values for each year in Table 11 are derived from tabulations for the months of February, May, August, and November. In this table the tidal current has been freed from the effects of the nontidal current, as explained in Section IV. *HH* and *LL* refer to the times of higher high water and lower low water, respectively, in Humboldt

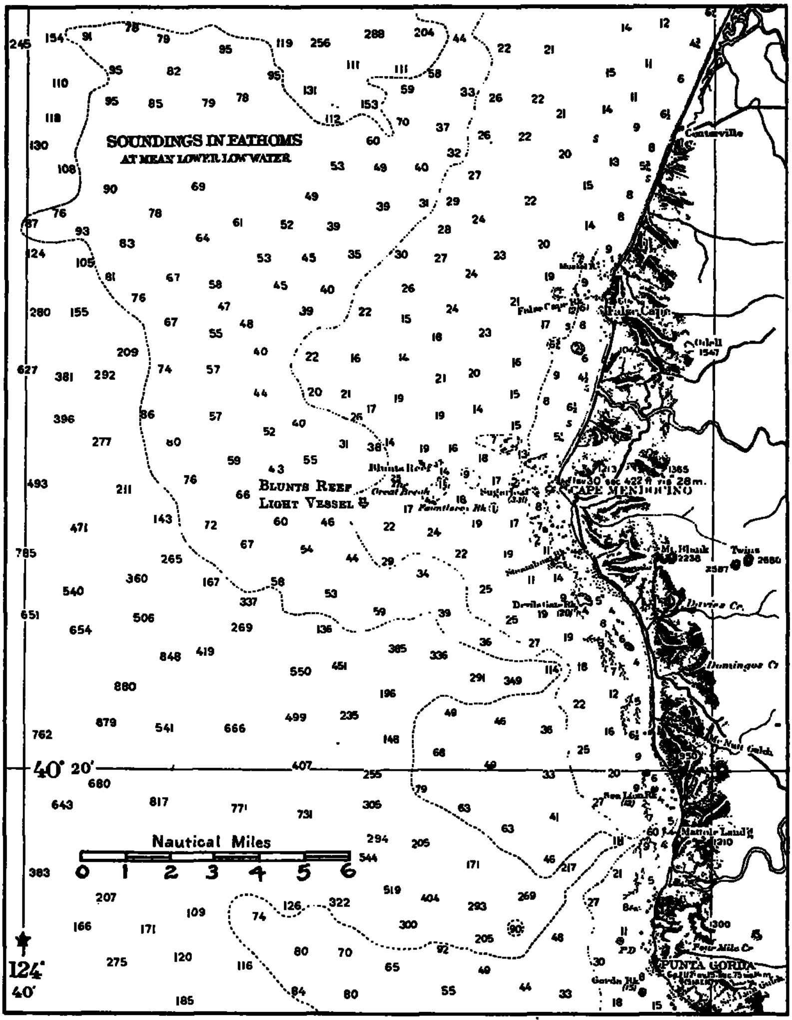

FIG. 15.—Location of Blunts Reef Light Vessel

Bay, while *H* and *L* refer to the times of lower high water and higher low water. The velocities are given in knots and the directions are true, not magnetic, and are reckoned from north as 0°; east, 90°; west, 270°. The final mean was derived by resolving the velocities for each year and adding algebraically.

TABLE 11.—*Mean tidal current, Blunts Reef Light Vessel*

[Referred to time of tide at Humboldt Bay]

Tidal hour	1919		1920		Mean	
	Velocity	Direction	Velocity	Direction	Velocity	Direction
	Knots	*Degrees*	*Knots*	*Degrees*	*Knots*	*Degrees*
HH−3	0.03	50	0.07	35	0.05	40
HH−2	.03	70	.05	10	.03	20
HH−1	.01	170	.05	45	.02	60
HH	.03	200	.02	5	.01	215
HH+1	.03	215	.04	215	.03	215
HH+2	.06	225	.05	210	.06	220
HH+3	.08	215	.10	190	.09	200
LL−3	.08	230	.11	190	.09	205
LL−2	.08	210	.09	190	.08	200
LL−1	.06	225	.08	195	.07	205
LL	.01	270	.03	220	.02	230
LL+1	.01	140	.01	100	.01	125
LL+2	.03	140	.01	55	.02	115
LL+3	.03	160	.06	50	.02	80
H−2	.01	280	.05	355	.03	340
H−1	.01	310	.03	365	.02	355
H	.02	345	.07	360	.04	355
H+1	.04	315	.08	10	.06	350
H+2	.07	340	.06	10	.06	350
L−2	.06	5	.02	55	.04	20
L−1	.07	10	.04	80	.05	35
L	.06	30	.02	115	.03	50
L+1	.04	25	.04	60	.04	45
L+2	.05	25	.02	345	.04	15

The velocities of the tidal current in Table 11 are so small that it is difficult to determine from the data of the table the characteristics of the current. In addition to Table 11 there are at hand also the results of an harmonic analysis for M_2 of a 29-day series from January 23 to February 20, 1916. From these results the current here appears to be slightly rotary, the strength of the current having a velocity of about 0.1 knot and the minimum current a velocity of 0.05 knot, flood setting northerly and ebb southerly.

NONTIDAL CURRENT

The nontidal current at Blunts Reef Light Vessel is given in Table 12 for each month of the period of observations. As previously explained, the nontidal current is derived by summing algebraically, in groups of 29 days, the observed hourly velocities and directions of the current after they had been resolved into north-and-south and east-and-west components. The velocities in the table are in knots and the directions are true, reckoned clockwise from north as zero. Unless otherwise noted, the first 29 days were used for each month except for the month of February, for which the last day of January was included when necessary to complete a 29-day group.

Table 12.—*Nontidal current, Blunts Reef Light Vessel; average velocity and direction*

Month	1915		1916		1918		1919		1920	
	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.
	Knots	*Deg.*	*Knots*	*Deg.*	*Knots*	*Deg.*	*Knots*	*Deg.*	*Knots*	*Deg.*
January	0.38	[1] 339	0.44	362			0.38	351	0.09	206
February	.60	344	.32	326			.12	299	.08	290
March	.29	206	.30	232			.21	245	.13	213
April	.26	[2] 204	.35	208			.35	212	.45	197
May			.39	202			.15	216	.42	192
June			.12	195			.17	200	.20	200
July							.11	200	.34	200
August	.37	214			0.18	209	.11	227	.11	222
September	.23	220			.11	238	.08	230	.16	222
October	.13	251			.24	224	.11	205	.19	228
November	.08	290			.11	223	.11	200	.30	336
December	.15	301			.14	220	.16	358	.17	304
Mean	.13	263	.13	251	.16	221	.09	241	.16	218

[1] For January, 1915, the data given are based on 12 days of observations, from the 18th to the 29th.
[2] For April, 1915, the data given are based on 16 days of observations, from the 1st to the 16th.

For each year given in Table 12 the resultant direction of the current is southwesterly. For the winter months, however, the direction of the current is northwesterly or northerly. Along this stretch of the coast during the winter months the wind is prevailingly from the southeast, while during the remainder of the year the prevailing wind is from the north. The wind, therefore, appears to account for the direction of the average monthly nontidal current at Blunts Reef Light Vessel. For the period of observations covered by Table 12 the velocity of the nontidal current averaged 0.12 knot, its direction being 236°.

WIND CURRENT

The results of a tabulation of the current accompanying winds from various directions are given in Table 13. In this tabulation the resolved velocities of the current were used. The wind directions used in the tabulations were those recorded by the observers on the light vessel and were, therefore, magnetic and uncorrected for deviation. As in the case of the tabulation for San Francisco Light Vessel, the corrections for variation and deviation were applied to the yearly means, which procedure assumes that the ship headed in the direction of the wind. The yearly means, corrected for variation and deviation, were further corrected to bring the various wind directions to the nearest true directions given in Table 13.

TABLE 13.—*Wind currents, Blunts Reef Light Vessel*

Wind from—	Year	Wind 10–19 Current No. of obs.	Vel.	Dir.	Wind 20–29 Current No. of obs.	Vel.	Dir.	Wind 30–39 Current No. of obs.	Vel.	Dir.	Wind 40–49 Current No. of obs.	Vel.	Dir.	Wind 50–59 Current No. of obs.	Vel.	Dir.
			Knots	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*
N	1915	279	0.38	202	101	0.55	200	25	0.62	202	29	1.06	199	—	—	—
	1916	422	.53	201	622	.62	201	111	.65	193	78	.85	194	12	1.10	194
	1918	522	.33	214	195	.46	206	78	.61	205	9	1.01	191	—	—	—
	1919	1170	.26	200	516	.30	196	112	.46	198	14	.40	190	18	.43	199
	1920	950	.35	195	964	.41	192	172	.54	190	59	.64	193	14	.62	188
Mean	—	3,343	.34	201	2,398	.45	198	498	.56	195	189	.79	194	44	.67	194
NNE	1915	672	.37	220	502	.50	213	34	.70	216	18	.65	203	—	—	—
	1916	222	.44	210	239	.67	211	54	.90	207	8	1.31	205	—	—	—
	1918	246	.39	218	98	.44	204	7	.51	183	—	—	—	—	—	—
	1919	690	.30	216	174	.44	208	35	.65	206	20	.90	213	—	—	—
	1920	794	.39	211	596	.44	203	56	.68	202	10	.46	194			
Mean	—	2,624	.36	215	1,609	.49	208	186	.73	206	56	.80	207	—	—	—
NE	1915	91	.41	219	20	1.14	219	—	—	—	—	—	—	—	—	—
	1916	9	.19	200	—	—	—	—	—	—	—	—	—	—	—	—
	1918	4	.15	298	—	—	—	—	—	—	—	—	—	—	—	—
	1919	9	.44	244	4	.69	228	—	—	—	—	—	—	—	—	—
	1920	47	.33	238	14	.24	210	—	—	—	—	—	—	—	—	—
Mean	—	160	.36	226	38	.76	219	—	—	—	—	—	—	—	—	—
ENE	1915	40	.31	247	9	.48	270	—	—	—	—	—	—	—	—	—
	1916	18	.21	289	—	—	—	—	—	—	—	—	—	—	—	—
	1918	—	—	—	6	.42	171	—	—	—	—	—	—	—	—	—
	1919	11	.35	293	—	—	—	—	—	—	—	—	—	—	—	—
	1920	32	.24	308	2	.25	252	—	—	—	—	—	—	—	—	—
Mean	—	101	.24	276	17	.30	239	—	—	—	—	—	—	—	—	—
E	1919	4	.82	289	—	—	—	—	—	—	—	—	—	—	—	—
	1920	10	.13	318	—	—	—	—	—	—	—	—	—	—	—	—
Mean	—	14	.32	297	—	—	—	—	—	—	—	—	—	—	—	—
ESE	1915	6	.68	333	—	—	—	—	—	—	2	1.56	335	—	—	—
	1916	16	.18	309	2	.67	242	—	—	—	—	—	—	—	—	—
	1918	3	.25	313	—	—	—	—	—	—	—	—	—	—	—	—
	1919	2	.76	223	—	—	—	—	—	—	—	—	—	—	—	—
	1920	5	.37	254	4	.28	341	—	—	—	—	—	—	—	—	—
Mean	—	32	.27	300	6	.27	286	—	—	—	2	1.56	335	—	—	—
SE	1915	17	.35	356	7	.51	287	2	.47	308	1	.41	124	—	—	—
	1916	43	.30	264	14	.58	335	—	—	—	—	—	—	—	—	—
	1918	19	.52	347	—	—	—	—	—	—	—	—	—	—	—	—
	1919	22	.22	272	—	—	—	—	—	—	—	—	—	—	—	—
	1920	14	.19	243	5	.35	223	—	—	—	—	—	—	—	—	—
Mean	—	115	.23	302	26	.41	311	2	.47	308	1	.41	124	—	—	—
SSE	1915	313	.33	360	373	.39	360	158	.61	349	188	.84	353	77	1.02	348
	1916	239	.48	348	238	.59	357	69	.84	348	125	1.03	352	21	1.20	362
	1918	117	.64	364	73	.68	362	26	.71	358	19	.87	353	9	.90	345
	1919	314	.34	351	300	.54	355	178	.69	355	98	.71	358	47	.66	367
	1920	475	.18	339	315	.29	345	251	.45	347	145	.50	351	97	.77	350
Mean	—	1,458	.33	352	1,299	.45	356	682	.60	351	575	.77	353	251	.86	353
S	1915	28	.28	353	34	.48	355	14	1.06	369	15	.76	355	6	1.40	359
	1916	59	.48	370	98	.55	362	34	.94	370	4	1.26	355	—	—	—
	1918	59	.51	372	40	.52	367	4	.94	368	—	—	—	—	—	—
	1919	171	.34	356	81	.41	360	17	.59	364	12	.95	363	—	—	—
	1920	112	.27	385	45	.21	376	33	.37	360	10	.57	364	2	.21	306
Mean	—	429	.35	367	298	.45	362	102	.71	367	41	.82	359	8	1.08	357

TABLE 13.—*Wind currents, Blunts Reef Light Vessel*—Continued

Wind from—	Year	Wind 10-19			Wind 20-29			Wind 30-39			Wind 40-49			Wind 50-59		
		Current			Current			Current			Current			Current		
		No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.
			Knots	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*
SSW	1915	37	0.37	368	50	0.51	354	8	0.79	374	10	0.99	374	1	0.76	358
	1916	81	.53	378	68	.79	379	13	1.35	384	18	1.04	379	5	1.52	375
	1918	10	.43	387	1	.63	365	2	.43	363						
	1919	39	.38	380	3	.33	373	2	.39	339	2	1.54	370			
	1920	58	.34	374	12	.39	373	1	.10	382				1	.61	372
Mean		225	.42	17	134	.59	12	26	.97	20	30	1.06	19	7	1.28	13
SW	1915	5	.88	25	4	1.12	12	4	1.06	24	4	1.10	5	5	.91	26
	1916	52	.35	21	27	.66	28									
	1918	20	.64	43												
	1919	17	.46	9												
	1920	7	.19	31	4	.67	7				2	.16	3			
Mean		101	.43	26	35	.71	23	4	1.06	24	6	.79	5	5	.91	26
WSW	1915	23	.35	32	23	.63	23	9	.72	11	4	.85	20	2	.98	35
	1916	40	.22	105	20	.44	57	7	.50	52						
	1918	8	.59	34	3	.72	33									
	1919	15	.19	73				2	.57	124	3	.73	70	1	.40	109
	1920	38	.09	77	13	.07	37	1	.22	49	2	.50	67			
Mean		124	.19	65	59	.43	36	19	.50	33	9	.67	44	3	.70	45
W	1916	10	.49	17	9	.62	24	1	.0							
	1918	6	.15	34												
	1919	5	.10	31							4	.35	167			
	1920	3	.53	112	5	.25	173	2	.65	45						
Mean		24	.19	51	14	.33	32	3	.43	45	4	.35	167			
WNW	1915	12	.09	2	13	.24	62				4	.32	48	4	.41	9
	1916	24	.36	63	4	.95	109	4	.55	107	1	.78	62			
	1918							1	.76	−1						
	1919	25	.36	184	5	.09	49									
	1920	22	.30	174	12	.32	37	5	.26	108						
Mean		81	.16	143	34	.28	68	10	.33	95	5	.40	52	4	.41	9
NW	1915	14	.51	206	8	.57	185	3	.89	8	3	1.34	14	1	1.20	21
	1916	17	.14	158	5	.43	150									
	1918	5	.22	90												
	1919	18	.15	158	5	.00	—									
	1920	17	.33	184	15	.39	168	1	.28	157	1	.28	157			
Mean		71	.24	182	33	.37	171	4	.61	11	4	.95	17	1	1.20	21
NNW	1915	266	.50	196	189	.63	189	50	.49	198	33	1.06	201			
	1916	112	.27	187	52	.38	194	18	.68	202	7	.56	229			
	1918	85	.38	211	22	.51	210	6	.80	201	4	.89	212			
	1919	145	.28	207	46	.57	198	26	.90	192	2	.70	172			
	1920	276	.26	211	162	.29	195	32	.39	185	12	.40	189			
Mean		884	.34	202	471	.47	193	132	.58	195	58	.83	202			

The velocities of the current in the means for the 16 directions of the wind in Table 13 exhibit less variation than did the corresponding currents at San Francisco Light Vessel. Again designating the winds in the various columns by the approximate means rather than by the two limiting values, it is seen that for the 15-mile wind the greatest velocity of the current is 0.43 knot, coming with the southwest wind, and the least 0.16 knot, coming with the west-northwest winds. A direct average of the mean velocities of Table 13 gives 0.31 knot for a 15-mile wind, 0.45 knot for a 25-mile wind, 0.63

knot for a 35-mile wind, 0.72 knot for a 45-mile wind, and 0.96 knot for a 55-mile wind.

For the 15 and 25 mile winds the observations on which the average currents of the preceding paragraph are based may be considered as sufficient to give a good determination. For the other wind velocities several directions are represented by too few observations to give good determinations of the resulting currents. In deriving the average current accompanying the winds of different velocities at San Francisco Light Vessel all results based on less than 10 observations were omitted; but since the tidal current at Blunts Reef Light Vessel is very weak we may use results based on fewer observations. Omitting the results based on less than five observations, Table 13 gives as the average current accompanying 35-mile winds, 0.62 knot, 45-mile winds 0.77 knot, and 55-mile winds 0.96 knot. In general, therefore, the velocity of the wind-driven current at Blunts Reef Light Vessel, in knots, is about 1¾ per cent the velocity of the wind in miles per hour, which compares with 1½ per cent found at San Francisco Light Vessel.

In regard to the direction of the wind-driven current Table 13 shows that the current at Blunts Reef Light Vessel generally sets to the right of the wind, except with winds from the southwest quadrant. Some of the results appear anomalous, especially those based on but few observations; as, for example, the current due to northwest winds with velocities of 30 miles and over. When based on but few observations the results may not even be approximately correct, for the direction of the current at any instant obviously does not necessarily depend on the direction of the wind at that instant.

As noted before, the prevailing winds along this stretch of the coast are from the southeast in winter and from the north during the remainder of the year. Taking the results for the south-southeast winds as giving the best determined values for the southerly winds, the deviation of the current from the wind is 15° to the right of the wind. Taking the results for the north-northwest, north, and north-northeast winds, the deviation is about 20° to the right of the wind. For the prevailing winds at Blunts Reef Light Vessel, therefore, the deviation of the current is from 15 to 20° to the right of the wind direction.

In discussing the nontidal current at Blunts Reef Light Vessel it was stated that the wind appeared to account for the direction of the average monthly nontidal current. In other words, at Blunts Reef Light Vessel there appears no permanent nontidal set, independent of the wind, such as found at San Francisco Light Vessel. This is borne out by the results in Table 13. Thus, the northerly winds bring about currents with practically the same velocities as the southerly winds, and the same statement holds for easterly and westerly winds.

VI. OBSERVATIONS ON COLUMBIA RIVER LIGHT VESSEL

LOCATION AND LENGTH OF SERIES

As its name implies, this light vessel is located off the entrance to Columbia River. It is anchored in 35 fathoms of water, about 8 miles from the coast and about the same distance southwesterly from the entrance to the Columbia River, in latitude 46° 10′ 45″ N., longitude 124° 10′ 35″ W.

Current observations on this light vessel were begun January 21, 1915, and continued for three months, to April 21, 1915. Another series began May 29, 1915, and continued to June 30, 1916. A third

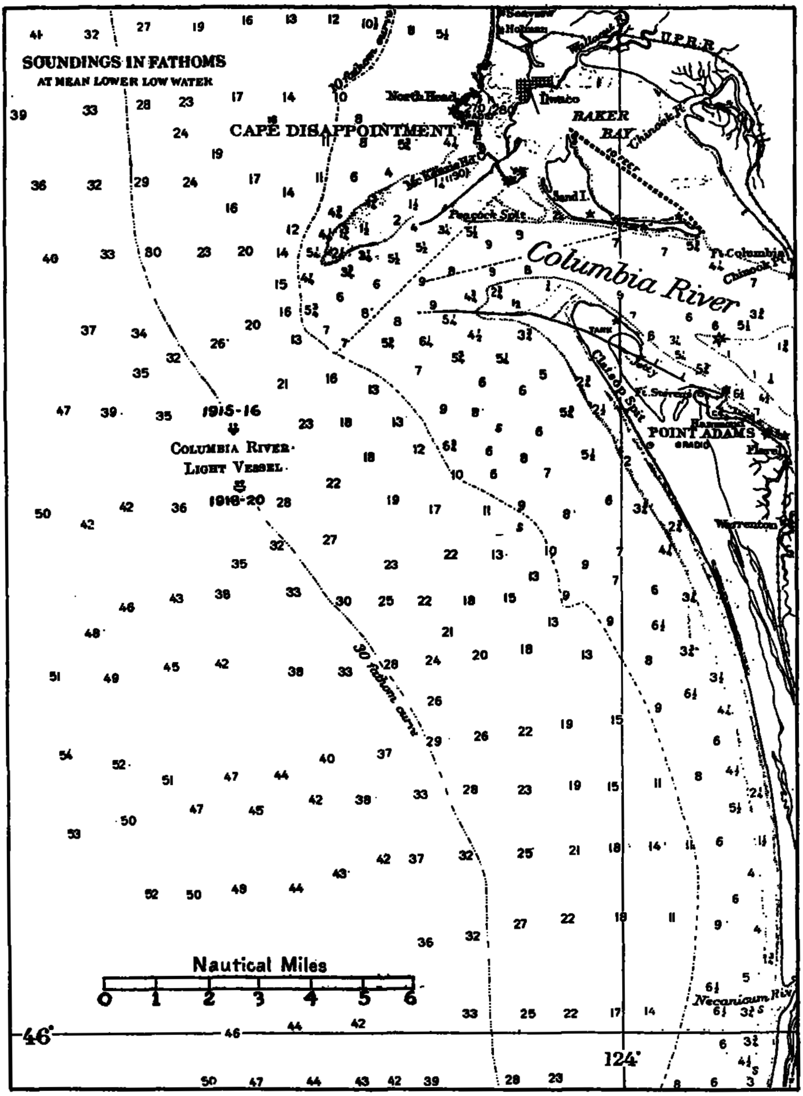

FIG. 16.—Location of Columbia River Light Vessel

series covers the period from November 1, 1918, to December 31, 1920.

In 1917 the position of the light vessel was changed. Previous to that time it had been anchored at a point about 1⅛ miles north of its later position. The two positions of the light vessel are indicated on Figure 16. Throughout the entire period the current observations were made by means of a logline, graduated for a run of 28 seconds, which interval was determined by means of a sand glass.

TIDAL CURRENT

The tidal current at Columbia River Light Vessel is of the rotary type with a velocity at strength of flood or ebb of about a quarter of a knot. The rotary character of the current, however, is generally masked by a nontidal current having an average velocity of half a knot or more, setting southwesterly. This nontidal current is due to the drainage from the enormous territory which finds its outlet to the sea through the Columbia River. Hence, the current at Columbia River Light Vessel generally sets southwesterly.

In deriving the tidal current at Columbia River Light Vessel the resolved hourly values of the current were tabulated with reference to the times of high and low water at Astoria, Oreg., in periods of 29 days, beginning the first of the month. The resulting mean hourly values were then plotted, as was also the nontidal current for the month. From this plotting the tidal current freed from the nontidal current was obtained for each tidal hour.

In Table 14 are given the velocities and directions of the tidal current for the years 1919 and 1920, as derived from tabulations for the months of February, May, August, and November. *HH* and *LL* refer, respectively, to the times of higher high water and lower low water at Astoria, Oreg., while *H* and *L* refer to the times of lower high water and higher low water. The velocities are given in knots and the directions are true, not magnetic, and are reckoned from north as 0°; east, 90°; west, 270°. The final mean was derived by resolving the values for each year and adding algebraically.

TABLE 14.—*Mean tidal current, Columbia River Light Vessel*

[Referred to time of tide at Astoria, Oreg.]

Tidal hour	1919		1920		Mean	
	Velocity	Direction	Velocity	Direction	Velocity	Direction
	Knots	*Degrees*	*Knots*	*Degrees*	*Knots*	*Degrees*
HH−3	0.15	351	0.21	352	0.18	351
HH−2	.16	7	.26	11	.21	10
HH−1	.21	28	.30	19	.25	24
HH	.23	38	.20	26	.22	34
HH+1	.17	45	.23	59	.20	53
HH+2	.10	88	.12	94	.11	91
HH+3	.09	148	.14	168	.12	160
LL−3	.21	198	.24	175	.22	186
LL−2	.24	213	.25	190	.24	202
LL−1	.14	214	.24	200	.19	205
LL	.18	257	.21	227	.19	240
LL+1	.18	263	.18	254	.18	258
LL+2	.12	284	.16	280	.14	282
LL+3	.17	28	.15	318	.13	351
H−2	.21	39	.20	18	.20	29
H−1	.21	51	.20	26	.20	41
H	.19	75	.17	71	.18	74
H+1	.20	108	.18	124	.19	115
H+2	.16	120	.26	157	.20	143
L−2	.23	196	.40	204	.32	201
L−1	.21	219	.40	217	.31	218
L	.21	245	.35	225	.28	232
L+1	.16	274	.19	255	.18	263
L+2	.18	313	.15	337	.16	325

Diagrammatically, the tidal current at Columbia River Light Vessel is shown in Figure 17, and it is seen at once that the tidal current here is rotary, turning clockwise, and that it has but little

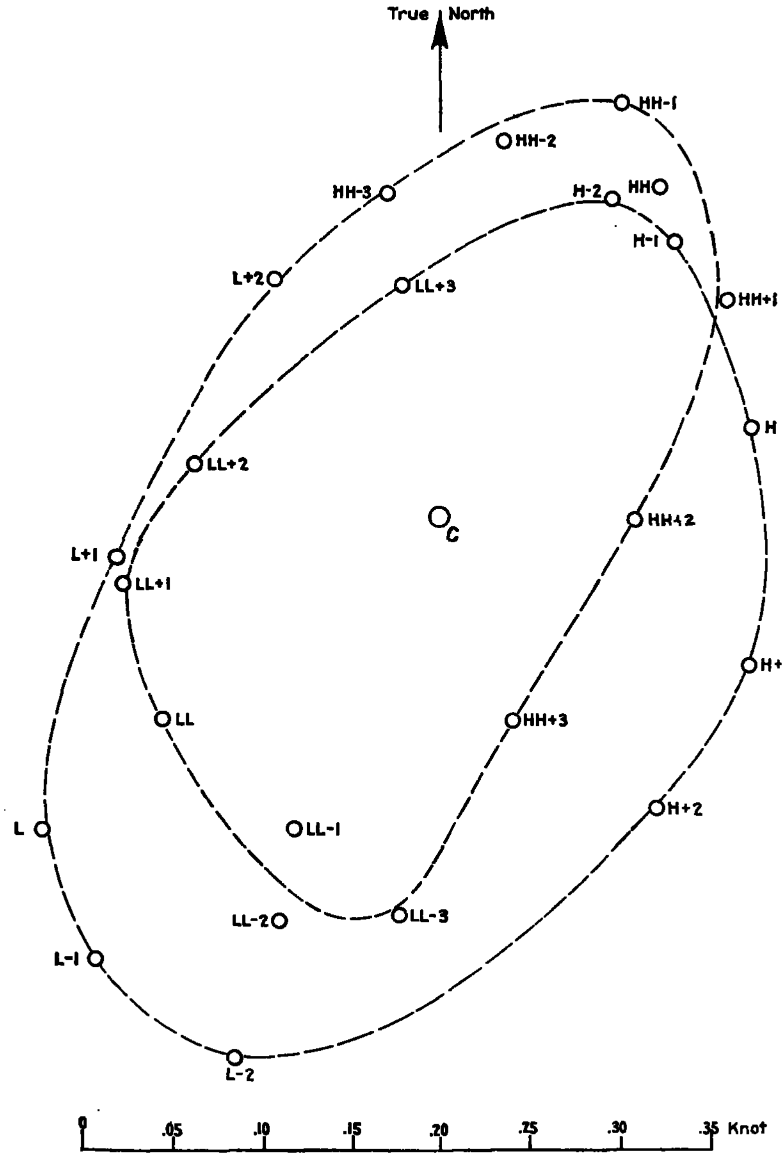

FIG. 17.—Mean tidal current curve, Columbia River Light Vessel

diurnal inequality. Strength of flood comes about the time of high water at Astoria, while strength of ebb comes about one hour before the time of low water. Flood sets northeasterly and ebb southwesterly, the velocity at strength being about 0.25 knot. The minimum current before flood or ebb has a velocity of about 0.15 knot and comes approximately two hours after high and low water at Astoria.

NONTIDAL CURRENT

The nontidal current at Columbia River Light Vessel for each month of the period of observations is given in Table 15. In this table, as in the previous ones, the nontidal current for each month was derived by summing algebraically the observed hourly velocities and directions of the current after they had been resolved into north-and-south and east-and-west components. Unless otherwise noted, the observations for the first 29 days were used for each month except for February, for which the last day of January was included when necessary to complete a 29-day group. The velocities in the table are in knots and the directions are true, reckoned clockwise from north as zero.

TABLE 15.—*Nontidal current, Columbia River Light Vessel; average velocity and direction*

Month	1915		1916		1918		1919		1920	
	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.
	Knots	*Deg.*	*Knots*	*Deg.*	*Knots*	*Deg.*	*Knots*	*Deg.*	*Knots*	*Deg.*
January			0.42	308			0.48	301	0.25	270
February	0.48	321	.65	295			.31	260	.42	213
March	.21	304	.43	302			.33	260	.16	233
April	.24	[1] 274	.54	258			.44	231	.60	207
May			.80	215			.39	258	.51	221
June	.82	227	.92	214			.66	224	.53	233
July	.48	239					.86	[2] 215	.47	230
August	.83	222					.43	207	.60	220
September	.53	225					.25	243	.20	296
October	.36	311					.31	212	.24	317
November	.42	[3] 319			0.33	284	.35	275	.36	307
December	.51	308			.25	279	.46	302	.53	320
Mean	.38	262	.55	265	.29	282	.36	246	.31	244

[1] For April, 1915, the data given are based on 21 days of observations, from the 1st to the 21st.
[2] For July, 1919, the data given are based on 17 days of observations, from the 15th to the 31st.
[3] For November, 1915, the data given are based on 26 days of observations, from the 4th to the 29th.

Being located off the entrance to Columbia River, it is to be expected that the very considerable drainage from the river would be a large factor in the nontidal current at the light vessel. Table 15 proves this to be the case, for the direction of the current is seen to be westerly every month. There is evidence, however, of a seasonal variation, the current setting southwesterly in the spring and summer months and northwesterly in the fall and winter months. This appears to be due to the wind along this part of the coast which is prevailingly from the northwest in the spring and summer months and from the east or southeast during the fall and winter months.

A seasonal variation is also exhibited by the velocity of the nontidal current, with a maximum in the summer months. This variation in velocity is undoubtedly to be ascribed to the seasonal variation in discharge through the Columbia River, which is at its maximum during the early summer months. For corresponding months the velocities in 1915 and 1916 are seen to be greater than in 1918 to 1920; but, as shown on Figure 16, the light vessel in 1915 and 1916 was nearer the mouth of the river.

WIND CURRENT

The results of a tabulation of the current accompanying winds from 16 directions at Columbia River Light Vessel are given in Table 16. In this tabulation the resolved velocities of the current were used and the procedure as outlined in Section III, under "Tabulation of light-vessel observations," was followed. The wind directions used in the tabulations were those recorded by the observers on the light vessel and were, therefore, magnetic and uncorrected for deviation. As was done in the tabulations for San Francisco and Blunts Reef Light Vessels, the corrections for variation and deviation were applied to the yearly means, this procedure tacitly assuming that the ship headed in the direction of the wind. The yearly means, corrected for variation and deviation, were further corrected to bring the various wind directions to the nearest true directions given in Table 16 by adding or subtracting the required number of degrees from both wind and current.

TABLE 16.—*Wind currents, Columbia River Light Vessel*

Wind from—	Year	Wind 10-19			Wind 20-29			Wind 30-39			Wind 40-49			Wind 40-59		
		Current			Current			Current			Current			Current		
		No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.
			Knots	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*
N	1915	178	0.81	224	111	1.10	214	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1916	136	1.12	228	71	1.38	224	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1918	2	.40	203	2	1.22	223	2	1.45	203	4	0.72	195	-----	-----	-----
	1919	376	.69	215	287	1.06	217	40	1.07	220	12	1.71	205	-----	-----	-----
	1920	372	.65	209	200	.93	216	2	.92	215	-----	-----	-----	-----	-----	-----
Mean	------	1,064	.74	217	671	1.06	217	44	1.08	219	16	1.46	204	-----	-----	-----
NNE	1915	23	.84	248	11	1.52	230	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1916	57	.71	233	3	.63	221	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1918	4	.65	255	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1919	215	.64	231	48	.78	220	1	.90	320	-----	-----	-----	-----	-----	-----
	1920	196	.62	206	84	.81	218	3	.64	268	-----	-----	-----	-----	-----	-----
Mean	------	495	.63	223	146	.85	220	4	.67	284	-----	-----	-----	-----	-----	-----
NE	1915	27	.66	234	2	1.70	243	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1916	33	.64	252	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1918	8	.68	222	2	.29	263	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1919	73	.47	232	16	.67	228	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1920	119	.32	217	17	.65	226	-----	-----	-----	-----	-----	-----	-----	-----	-----
Mean	------	260	.44	231	37	.69	230	-----	-----	-----	-----	-----	-----	-----	-----	-----
ENE	1915	106	.67	263	30	.61	280	2	.86	286	-----	-----	-----	-----	-----	-----
	1916	65	.54	262	32	.80	285	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1918	43	.70	233	35	.59	249	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1919	173	.42	235	118	.46	248	72	.52	283	32	.64	297	3	0.64	302
	1920	286	.35	243	118	.29	251	9	.16	353	4	.40	361	-----	-----	-----
Mean	------	673	.45	247	333	.44	259	83	.48	285	36	.59	301	3	.64	302
E	1915	170	.54	287	299	.65	288	35	.79	294	-----	-----	-----	-----	-----	-----
	1916	81	.68	281	225	.71	288	64	.76	293	57	.82	301	7	.79	287
	1918	109	.27	291	71	.38	287	18	.33	265	17	.55	316	-----	-----	-----
	1919	215	.38	281	234	.43	283	60	.48	280	29	.62	800	-----	-----	-----
	1920	232	.30	263	210	.45	284	63	.49	299	1	1.20	238	-----	-----	-----
Mean	------	807	.40	280	1,039	.55	286	240	.58	291	104	.71	302	7	.79	287

TABLE 16.—*Wind currents, Columbia River Light Vessel*—Continued

Wind from—	Year	Wind 10-19			Wind 20-29			Wind 30-39			Wind 40-49			Wind 40-59		
		Current			Current			Current			Current			Current		
		No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.
			Knots	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*
ESE	1915	215	0.45	280	127	0.69	314	5	0.68	278	----	----	----	----	----	----
	1916	85	.55	288	56	.65	291	3	1.60	295	5	1.51	308	1	1.20	298
	1918	77	.23	284	30	.29	257	3	.53	329	----	----	----	----	----	----
	1919	199	.32	271	64	.54	316	4	.97	261	----	----	----	----	----	----
	1920	218	.22	288	72	.53	309	7	.64	301	----	----	----	----	----	----
Mean	------	794	.34	281	339	.59	307	22	.78	289	5	1.51	308	1	1.20	298
SE	1915	41	.41	324	38	.72	315	1	1.00	322	----	----	----	----	----	----
	1916	14	.51	285	13	.60	319	2	.45	299	2	.94	275	----	----	----
	1918	12	.23	276	4	.51	310	3	.21	312	4	.62	362	----	----	----
	1919	51	.44	311	14	.85	314	2	.74	321	----	----	----	----	----	----
	1920	57	.36	281	17	.62	289	----	----	----	4	.34	329	----	----	----
Mean	------	175	.38	301	86	.68	311	8	.50	315	10	.45	327	----	----	----
SSE	1915	284	.33	316	272	.61	341	63	.81	344	44	.96	347	13	1.34	346
	1916	148	.49	301	92	.72	319	18	.70	352	17	1.07	323	5	1.76	343
	1918	18	.30	280	54	.31	329	14	.46	362	36	.57	348	5	.77	372
	1919	222	.32	317	229	.55	338	81	.72	341	46	.76	352	----	----	----
	1920	198	.32	334	198	.33	341	62	.46	359	71	.72	345	7	.92	358
Mean	------	870	.34	316	845	.52	336	238	.65	347	214	.77	345	30	1.20	350
S	1915	151	.28	335	215	.59	353	36	.97	358	21	1.06	355	3	1.21	362
	1916	108	.55	304	145	.64	345	56	1.09	346	25	1.06	356	4	1.26	348
	1918	26	.28	309	43	.40	348	28	.48	359	54	.62	363	10	.99	363
	1919	168	.32	323	218	.49	340	103	.66	352	126	.61	362	13	.75	374
	1920	273	.45	335	336	.53	349	173	.91	325	90	.74	325	8	.72	357
Mean	------	726	.38	326	962	.54	347	396	.82	339	316	.69	350	38	.89	3
SSW	1915	223	.34	317	104	.57	350	17	.91	354	23	1.10	360	8	.83	377
	1916	112	.52	307	183	.56	347	46	.94	358	14	1.19	362	1	1.75	351
	1918	20	.26	284	27	.38	338	9	.59	353	4	.62	354	----	----	----
	1919	192	.18	302	165	.32	332	60	.42	354	56	.61	375	12	.96	378
	1920	175	.22	306	176	.42	341	44	.49	362	23	.64	355	10	1.16	347
Mean	------	722	.29	309	655	.45	343	176	.63	357	120	.77	5	31	.98	5
SW	1915	91	.40	346	68	.54	364	13	.87	357	5	.96	360	3	1.63	368
	1916	78	.47	279	113	.57	337	41	.61	344	5	1.44	357	----	----	----
	1918	14	.16	353	16	.23	360	6	.11	334	6	.32	338	----	----	----
	1919	72	.22	301	66	.48	344	24	.68	342	14	.98	355	3	.90	356
	1920	155	.24	323	84	.48	339	17	.48	372	19	.57	356	----	----	----
Mean	------	410	.28	315	347	.50	345	101	.60	349	49	.78	355	6	1.26	4
WSW	1915	141	.28	319	86	.37	307	12	.42	363	27	.49	379	----	----	----
	1916	116	.35	270	127	.25	302	29	.61	347	10	.54	389	----	----	----
	1918	15	.34	303	20	.33	313	----	----	----	----	----	----	----	----	----
	1919	152	.31	291	99	.29	268	56	.37	288	42	.17	300	8	.60	124
	1920	297	.23	255	94	.14	379	37	.09	86	15	.32	337	----	----	----
Mean	------	721	.26	280	426	.23	302	134	.26	325	94	.27	357	8	.60	124
W	1915	54	.43	270	15	.33	328	----	----	----	----	----	----	----	----	----
	1916	60	.76	219	47	.35	236	7	.35	276	1	.80	331	----	----	----
	1918	20	.21	332	14	.50	180	----	----	----	----	----	----	----	----	----
	1919	50	.31	239	34	.40	211	18	.29	252	4	.62	279	----	----	----
	1920	123	.26	240	40	.34	221	18	.49	209	23	.33	284	----	----	----
Mean	------	307	.35	241	150	.32	224	43	.34	232	28	.38	286	----	----	----
WNW	1915	122	.63	238	34	.55	218	----	----	----	----	----	----	----	----	----
	1916	79	.78	229	81	.96	215	8	.98	238	2	.43	327	----	----	----
	1918	15	.60	269	6	1.16	239	----	----	----	----	----	----	----	----	----
	1919	126	.48	228	79	.61	222	24	.66	213	21	.84	234	----	----	----
	1920	269	.39	224	85	.64	217	43	.95	204	20	1.10	194	4	1.15	176
Mean	------	611	.51	230	285	.72	218	75	.84	210	43	.86	213	4	1.15	176

TABLE 16.—*Wind currents, Columbia River Light Vessel*—Continued

Wind from—	Year	Wind 10-19			Wind 20-29			Wind 30-39			Wind 40-49			Wind 50-59		
		Current			Current			Current			Current			Current		
		No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.
			Knots	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*
NW	1915	76	0.72	223	24	0.73	219	10	1.12	196	4	1.46	169	-----	-----	-----
	1916	90	1.04	233	59	1.13	222	8	1.69	215	-----	-----	-----	-----	-----	-----
	1918	-----	-----	-----	5	1.38	204	4	.82	201	6	.78	203	-----	-----	-----
	1919	98	.61	215	62	.70	220	14	1.57	224	16	1.32	218	-----	-----	-----
	1920	190	.38	220	88	.86	210	44	1.15	208	25	1.35	211	15	0.79	175
Mean	-----	454	.61	224	238	.88	216	80	1.25	211	51	1.35	209	15	.79	175
NNW	1915	178	.81	224	111	1.10	214	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1916	385	1.06	231	217	1.26	222	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1918	25	.45	231	12	.87	230	2	1.02	242	2	.75	196	-----	-----	-----
	1919	742	.66	219	414	.89	219	60	1.02	215	22	1.26	203	-----	-----	-----
	1920	752	.64	218	368	.95	216	67	1.12	204	15	1.06	185	-----	-----	-----
Mean	-----	2,082	.73	222	1,122	1.00	218	129	1.06	209	39	1.14	196	-----	-----	-----

It will be convenient, as before, to designate the wind velocities in the various columns of Table 16 by their approximate means rather than by the two limiting values. Taking a direct average of the mean velocities of the current in the table, the 15-mile wind gives a current of 0.45 knot; 25-mile wind, 0.63 knot; 35-mile wind, 0.70 knot; 45-mile wind, 0.83 knot; 55-mile wind, 0.95 knot. These values give a relation of current to wind varying from very nearly 3 per cent for the 15-mile wind to 2 per cent for the 55-mile wind.

For any given wind velocity, however, the currents in Table 16 show a very considerable deviation from the average value, varying with the direction of the wind. Thus, a wind of 15 miles per hour is accompanied by a current of 0.74 knot when blowing from the north; but when it blows from the west-southwest the current is only 0.26 knot. In general, it is seen that northerly winds bring about the strongest currents while southwesterly winds bring about the weakest currents. This, obviously, is due to the nontidal current arising from the drainage waters setting seaward through the Columbia River.

For each of the wind directions listed in Table 16, with but few exceptions in the case of southwesterly and westerly winds, the current as derived from the 1915 and 1916 observations is greater than that from the 1918 to 1920 observations for corresponding wind velocities. In part this difference may be due to differences in estimating the strength of the wind or to differences in the details of making the observations, but principally this difference arises from the difference in the positions of the light vessel during the two periods. This is borne out by the fact that with southwesterly and westerly winds the current derived from the 1918 to 1920 observations frequently is the greater.

As regards the direction of the wind-driven current at Columbia River Light Vessel, Table 16 shows that this is southwesterly with northerly winds and northwesterly with southerly winds. The deflection of the current from the direction of the wind is therefore to the right with northerly winds and to the left with southerly winds.

This difference in deflection of the current from the wind direction must be ascribed in large part to the nontidal current from the Columbia River, which at the light vessel sets southwesterly. Thus, the tabulation for the northwest wind gives the following results: With a 15-mile wind the direction of the current is 89° to the right of the wind; 25-mile wind, current 81° to the right; 35-mile wind, current 76° to the right; 45-mile wind, current 74° to the right; 55-mile wind, current 40° to the right. The deflection to the right becomes less as the wind current becomes greater, counterbalancing the southwesterly set of the river current. The results for the southeast wind give similar indications. With a 15-mile wind the direction of the current is 14° to the left of the wind; 25-mile wind, current 4° to the left; 35-mile wind, current in direction of wind; 45-mile wind, current 12° to the right of wind.

To derive the current at Columbia River Light Vessel due to wind alone it is necessary to free the results in Table 16 from the effects of the nontidal current due to river discharge and other nonwind agencies. As a first approximation it will be sufficient to subtract the average nontidal current during the entire period of observations from the mean values of Table 16. From Table 15 the average nontidal current for the period of observations is determined as 0.35 knot, setting 253° or S73° W. Subtracting this current graphically from the mean values of the current for the various wind directions and velocities in Table 16, the values in Table 17 are derived.

TABLE 17.—*Wind currents, Columbia River Light Vessel, freed from average nontidal current*

Wind from—	Wind 10–19			Wind 20–29			Wind 30–39			Wind 40–49			Wind 50–59		
	Current			Current			Current			Current			Current		
	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.
		Knots	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*
N	1,064	0.51	194	671	0.80	202	44	0.81	205	16	1.25	192			
NNE	495	.38	193	146	.59	201	4	.41	310						
NE	260	.18	182	37	.40	210									
ENE	673	.11	227	333	.10	280	83	.28	331	36	.42	337	3	0.49	335
E	807	.18	341	1,039	.32	323	240	.36	328	104	.55	330	7	.54	308
ESE	794	.17	1	339	.48	343	22	.54	311	5	1.35	320	1	.99	312
SE	175	.30	2	86	.58	342	8	.46	358	10	.49	11			
SSE	870	.36	16	845	.58	12	238	.76	14	214	.85	9	30	1.28	5
S	726	.44	17	962	.66	19	396	.87	3	316	.81	15	38	1.06	21
SSW	722	.31	22	655	.57	21	176	.78	22	120	.96	25	31	1.15	20
SW	410	.33	25	347	.62	19	101	.72	18	49	.91	17	6	1.42	17
WSW	721	.17	29	426	.27	33	134	.37	31	94	.49	41	8	.85	106
W	307	.08	157	150	.18	138	43	.13	146	28	.21	352			
WNW	611	.23	194	285	.48	193	75	.63	188	43	.64	192	4	1.11	158
NW	454	.35	194	238	.64	197	80	1.01	198	51	1.02	195	15	.79	149
NNW	2,082	.47	199	1,122	.74	202	129	.84	192	39	.99	178			

Obviously Table 17 can give but a first or rough approximation to the true wind current, for the procedure employed in deriving the values of the table implies that the nontidal current has a constant velocity throughout the year, which Table 15 shows to be not the case. The figures in the various wind-velocity columns of Table 17 show as wide variations as those in Table 16, and in some cases even wider; but the average velocities agree better with those derived at the other light vessels. For the 15-mile wind Table 17 gives an average velocity of the current of 0.29 knot; 25-mile wind, 0.50 knot; 35-mile wind, 0.60 knot; 45-mile wind, 0.78 knot; 55-mile wind, 0.97 knot. The current is therefore 2.2 per cent of the 15-mile wind, 2.3 per cent of the 25-mile wind, and 2 per cent of the 35, 45, and 55 mile winds.

The direction of the current for the various wind directions in Table 17 is in most cases to the right of the wind. The mean deflection is 23° to the right for the 15-mile wind, 25° to the right for the 25-mile wind, 29° to the right for the 35-mile wind, 19° to the right for the 45-mile wind, and 26° to the right for the 55-mile wind, an average deflection, therefore, to the right of the wind of 24°. The deflection to the left of the wind shown by the current for the north-northeast and northeast winds is undoubtedly due to the imperfect elimination of the nontidal current. The deflection to the left shown by the currents for the southwest and west-southwest winds was found also for these winds from the observations on the other light vessels discussed, as shown in Tables 10 and 13.

VII. OBSERVATIONS ON UMATILLA REEF LIGHT VESSEL

LOCATION AND LENGTH OF SERIES

Umatilla Reef Light Vessel is situated off the coast of northern Washington. It is anchored in 25 fathoms of water about 4 miles west of Cape Alava, in latitude 48° 10′ 03″ N. and longitude 124° 50′ 25″ W. The location of the light vessel is shown in Figure 18.

The first series of current observations on Umatilla Reef Light Vessel was made in 1901, from June 8 to July 6. A second series began on May 1, 1915, and continued for six months to October 31. A third series covers the period from December 25, 1918, to December 31, 1920. In all, the three series comprise 31 months of observations. The observations were made hourly with a log line and a 15-foot pole weighted with sufficient sheet lead to submerge all but 1 foot of the staff. Prior to March 6, 1920, the observation interval was 28 seconds, this interval being determined by a sand glass; after that date the observation interval was 60 seconds and was determined by means of a stop watch.

TIDAL CURRENT

The tidal current at Umatilla Reef Light Vessel is only slightly rotary and has a velocity at strength of flood or ebb of about one-quarter of a knot. The velocities and directions of the tidal current for the years 1919 and 1920 as derived from tabulations for the months of February, May, August, and November are given in Table 18. In deriving the values for this table the resolved hourly values of the current were tabulated with reference to the times of high and low water at Astoria, Oreg., in periods of 29 days, beginning with the first of the month. The resulting mean hourly values for each of the four months were then plotted, as was also the average nontidal

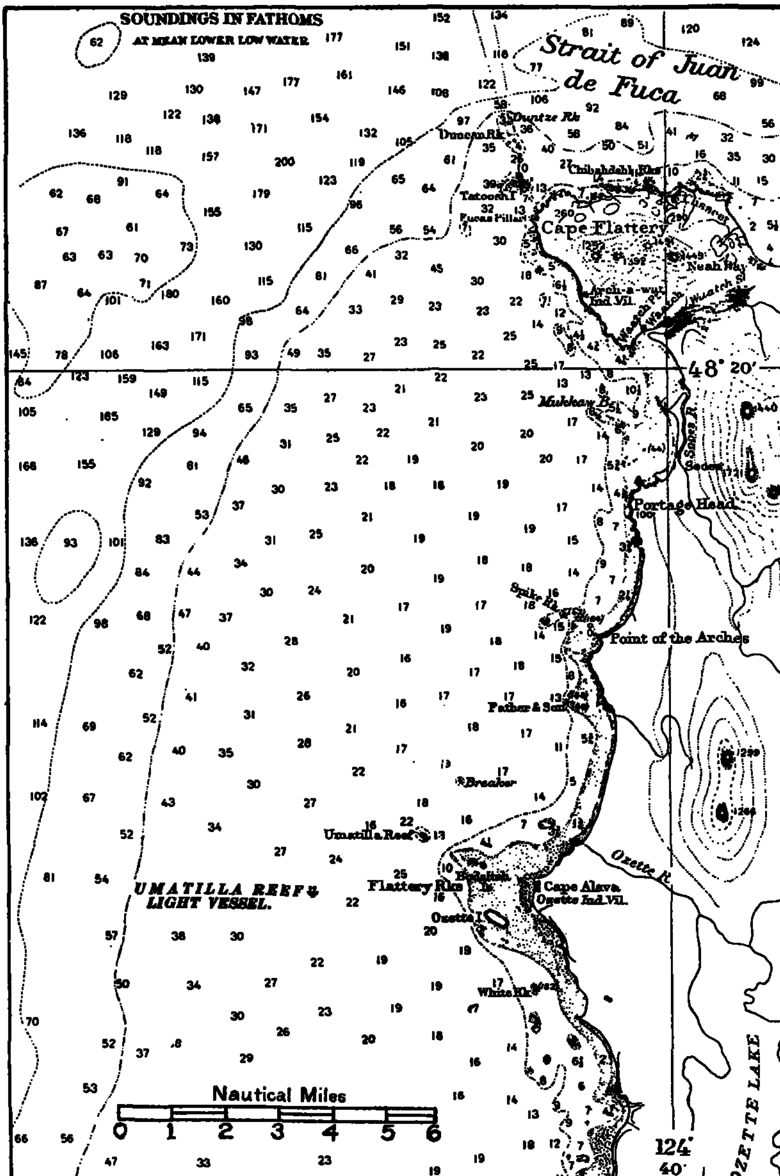

FIG. 18.—Location of Umatilla Reef Light Vessel

current for each of these months, and from this plotting the tidal current freed from the nontidal current was obtained for each tidal hour. In the table, *HH* and *LL* refer, respectively, to the times of higher high water and lower low water at Astoria, Oreg., while *H* and *L* refer to the times of lower high water and higher low water. The velocities are given in knots and the directions are true, reckoned from north as 0°; east, 90°; south, 180°; west, 270°. The mean for the two years given in the last column was derived by resolving the corresponding values for each year and adding algebraically.

TABLE 18.—*Mean tidal current, Umatilla Reef Light Vessel*

[Referred to time of tide at Astoria, Oreg.]

Tidal hour	1919		1920		Mean	
	Velocity	Direction	Velocity	Direction	Velocity	Direction
	Knots	*Degrees*	*Knots*	*Degrees*	*Knots*	*Degrees*
HH−3	0.12	180	0.10	155	0.11	169
HH−2	.06	294	.02	225	.04	278
HH−1	.16	334	.11	325	.13	329
HH	.22	331	.22	331	.22	331
HH+1	.21	338	.23	329	.22	334
HH+2	.17	349	.21	322	.18	334
HH+3	.12	334	.10	312	.11	325
LL−3	.05	214	.06	255	.05	235
LL−2	.18	181	.17	169	.18	175
LL−1	.28	178	.29	170	.28	174
LL	.37	177	.33	162	.35	170
LL+1	.35	171	.35	160	.35	166
LL+2	.26	179	.28	156	.26	167
LL+3	.16	179	.15	161	.15	171
H−2	.06	318	.06	301	.06	309
H−1	.23	344	.20	338	.22	341
H	.29	360	.33	344	.30	352
H+1	.33	3	.36	347	.34	354
H+2	.29	9	.37	352	.32	360
L−2	.13	61	.11	23	.11	43
L−1	.15	140	.06	136	.11	139
L	.22	164	.18	138	.19	152
L+1	.25	174	.20	147	.22	162
L+2	.16	183	.20	157	.17	168

Figure 19, based on the data in the last two columns of Table 18, gives a diagrammatic representation of the tidal current at Umatilla Reef Light Vessel, the distance and direction from point *C* to the various points on the periphery of the curve giving, respectively, the velocity and direction of the tidal current at those times. The diagram shows that, although the tidal current here is in general but slightly rotary, the direction of rotation is definitely clockwise. Strength of flood is seen to come about one hour after high water at Astoria and strength of ebb about one hour after low water. The diagram also shows the existence of considerable diurnal inequality, the greater flood coming with lower high water at Astoria and the greater ebb with lower low water. On the average, the velocity of the tidal current at strength of flood or ebb is 0.28 knot, while the minimum current before flood or ebb is 0.05 knot, coming two hours before the times of high or low water at Astoria. At strength of flood the tidal current sets approximately north 15° west, while at strength of ebb it sets south 15° east.

The 29-day series of observations made in 1901 had been analyzed harmonically and the M_2 current ellipse derived. This gave at strength of flood a velocity of 0.34 knot setting north 13° west and coming 45 minutes after high water at Astoria. The minimum current before flood from this current ellipse was 0.04 knot. An M_2 current ellipse based on an harmonic analysis of 162½ days of observations, from May 1 to October 10, 1915, gave strength of flood 55 minutes after high water at Astoria with a velocity of 0.26 knot, setting north 23° west, and a minimum before flood of 0.05 knot.

The tidal current at Umatilla Reef Light Vessel, having at strength a velocity of but little over a quarter of a knot, is generally masked by nontidal currents.

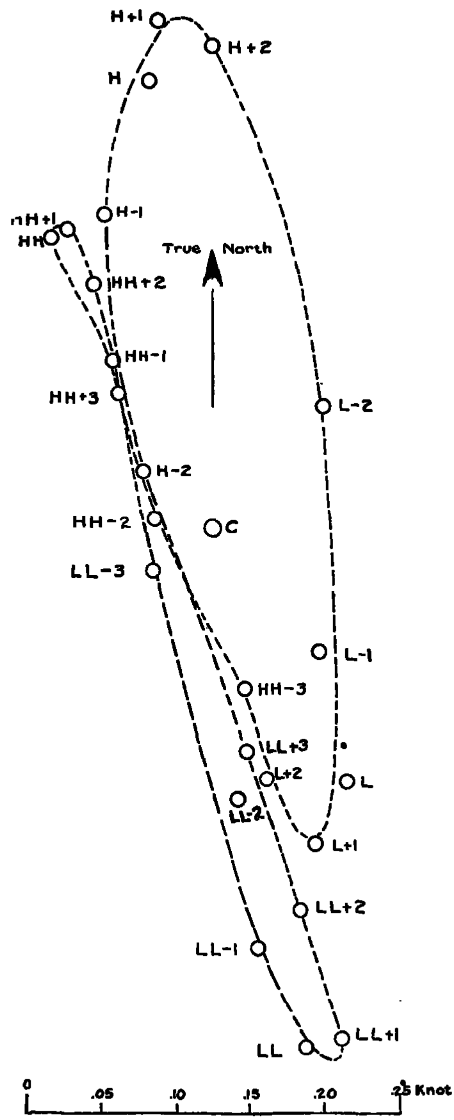

FIG. 19.—Mean tidal current curve, Umatilla Reef Light Vessel

NONTIDAL CURRENT

The nontidal current at Umatilla Reef Light Vessel for each month of the period of observations is given in Table 19. For each month the nontidal current was derived by summing algebraically the resolved values (resolved into north-and-south and east-and-west components) of the observed hourly velocities and directions of the current. Unless otherwise noted, the observations for the first 29 days were used for each month except in the case of February, for which month the last day of January was included when necessary to complete a 29-day group. The velocities in the table are in knots, and the directions are true, reckoned clockwise from north as zero.

A seasonal variation in the direction of the nontidal current at Umatilla Reef Light Vessel is evident from Table 19. In general, it may be said that in the winter months the nontidal current here sets northerly, while in the summer months it sets southerly. This appears to be due to the winds, which in winter are prevailingly from the east and southeast and in summer from the west and northwest.

TABLE 19.—*Nontidal current, Umatilla Reef Light Vessel; average velocity and direction*

Month	1901		1915		1919		1920	
	Velocity	Direction	Velocity	Direction	Velocity	Direction	Velocity	Direction
	Knots	*Degrees*	*Knots*	*Degrees*	*Knots*	*Degrees*	*Knots*	*Degrees*
January					0.86	354	0.72	348
February					.65	357	.07	220
March					.47	355	.34	356
April					.50	359	.35	162
May			0.67	344	.11	152	.37	167
June	0.50	[1] 173	.37	163	.57	168	.26	364
July			.26	172	.59	168	.45	170
August			.26	179	.27	184	.44	164
September			.22	188	.03	249	.63	349
October			.59	357	.16	152	.84	352
November					.79	346	.48	[2] 346
December					.90	345	1.26	[3] 354
Mean			.03	305	.20	354	.22	354

[1] For June, 1901, the data given are based on 29 days of observations, from June 8 to July 6.
[2] For November, 1920, the data are based on 26 days of observations, from the 1st to the 26th.
[3] For December, 1920, the data are based on 24 days of observations, from the 6th to the 29th.

Table 19 shows that during the winter months, when the nontidal current sets northerly, it has a greater velocity than during the summer months, when it sets southerly. On the average the northerly setting nontidal current has a velocity of two-thirds of a knot, while the southerly setting current has a velocity of one-third of a knot. This feature, too, attests the dependence of the nontidal current at Umatilla Reef on the wind, for the northerly winds are of less frequent occurrence and of lesser velocity than the southerly winds, as a glance at Table 20 shows. For the period covered by the observations in 1915, 1919, and 1920 the nontidal current averaged 0.17 knot, setting 353°.

WIND CURRENT

The results of a tabulation of the current accompanying winds from 16 directions at Umatilla Reef Light Vessel are given in Table 20. In the tabulation the observations for the years 1915, 1919, and 1920 were used. The procedure followed in deriving the results given in the table is the same as that made use of in the similar tables for the other light vessels and explained in detail in Section IV, discussing the wind current at San Francisco Light Vessel.

TABLE 20.—*Wind currents, Umatilla Reef Light Vessel*

Wind from—	Year	Wind 10-19			Wind 20-29			Wind 30-39			Wind 40-49			Wind 50-59		
		Current			Current			Current			Current			Current		
		No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Di·.
			Knots	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*
N	1915	95	0.40	199												
	1919	35	.31	216	4	0.22	176									
	1920	35	.18	215	10	.16	65									
Mean		165	.33	204	14	.11	98									

TABLE 20.—*Wind currents, Umatilla Reef Light Vessel*—Continued

Wind from—	Year	Wind 10-19			Wind 20-29			Wind 30-39			Wind 40-49			Wind 50-59		
		Current			Current			Current			Current			Current		
		No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.
			Knots	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*
NNE	1915	21	0.12	216												
	1919	75	.33	214	5	0.72	206									
	1920	47	.26	188	3	.46	248									
Mean		143	.27	206	8	.59	217									
NE	1915	20	.26	159												
	1919	34	.19	203	5	.17	167									
	1920	51	.34	179	4	.76	235									
Mean		105	.27	181	9	.38	222									
ENE	1915	20	.59	316												
	1919	141	.30	311	102	.55	312	7	0.71	315	19	0.81	290	4	0.52	295
	1920	108	.31	311	34	.30	295	13	.50	252						
Mean		269	.33	312	136	.48	309	20	.49	279	19	.81	290	4	.52	295
E	1915	56	.74	295	13	.62	296									
	1919	75	.42	320	23	.81	342	3	1.50	321						
	1920	52	.70	303	25	1.00	337	2	.85	313	7	.78	342			
Mean		183	.59	305	61	.80	332	5	1.24	319	7	.78	342			
ESE	1915	64	.26	286	32	.56	304	3	1.24	302						
	1919	211	.28	325	56	.87	338	7	.89	333						
	1920	174	.27	338	34	.69	337	3	1.30	336						
Mean		449	.26	325	122	.72	331	13	1.03	326						
SE	1915	162	.74	314	67	1.03	313	8	1.80	315	7	1.37	337			
	1919	121	.66	343	81	.94	347	8	1.44	342	1	1.20	341			
	1920	218	.59	344	92	1.21	345	21	1.51	343	19	1.98	346			
Mean		501	.64	333	240	1.03	337	37	1.50	335	27	1.79	344			
SSE	1915	228	.26	328	55	.85	351	2	1.93	365	2	2.02	362	5	1.58	357
	1919	449	.43	348	331	1.17	351	144	1.24	351	235	1.40	350	4	1.76	352
	1920	431	.44	350	353	.91	348	191	1.24	347	222	1.40	345	18	1.47	348
Mean		1,108	.40	346	739	1.02	350	337	1.24	349	459	1.40	348	27	1.53	350
S	1915	155	.42	358	39	.99	357	9	1.38	363	27	1.29	351	22	1.64	348
	1919	118	.72	361	169	.91	363	36	1.39	358	32	1.63	356	1	1.40	362
	1920	195	.47	361	106	.82	356	30	1.51	353	6	1.06	361	7	1.24	350
Mean		468	.52	360	314	.89	360	75	1.43	356	65	1.43	354	30	1.53	350
SSW	1915	82	.28	370				6	1.05	358	1	1.02	372	1	1.70	355
	1919	128	.34	387	40	1.30	381	28	1.80	361	9	1.47	364			
	1920	175	.71	359	67	.98	354	23	1.02	360	19	1.12	364	1	1.30	341
Mean		385	.49	367	107	1.07	366	57	1.41	360	29	1.23	364	2	1.49	349
SW	1915	61	.02	385	20	.54	381	1	1.03	348						
	1919	56	.77	367	25	.94	374	15	1.72	363	9	1.67	365	1	2.00	363
	1920	77	.63	365	39	.93	366	22	1.30	358	18	1.71	361			
Mean		194	.48	366	84	.84	371	38	1.46	360	27	1.70	362	1	2.00	363
WSW	1915	79	.04	119	13	.51	363	6	1.81	348	2	1.35	362			
	1919	198	.30	22	70	.81	371	31	1.00	375	13	1.06	367			
	1920	182	.48	5	78	.66	367	29	.52	391	21	1.11	375			
Mean		459	.31	373	161	.71	369	66	.84	374	36	1.10	371			
W	1915	67	.13	41	15	.92	353	1	1.44	367						
	1919	45	.17	6	23	.74	363	7	.90	373	12	1.37	371			
	1920	105	.35	3	24	.63	387	17	.40	396	10	.22	356			
Mean		217	24	369	62	.72	368	25	.57	383	22	.84	369			

TABLE 20.—*Wind currents, Umatilla Reef Light Vessel*—Continued

Wind from—	Year	Wind 10-19			Wind 20-29			Wind 30-39			Wind 40-49			Wind 50-59		
		Current			Current			Current			Current			Current		
		No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.
			Knots	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*
WNW	1915	132	0.40	194	20	0.46	152	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1919	294	.27	155	115	.23	38	42	0.42	9	5	0.54	109	-----	-----	-----
	1920	436	.12	137	81	.41	15	49	.44	26	64	.33	132	-----	-----	-----
Mean	-----	862	.20	161	216	.25	33	91	.43	18	69	.34	129	-----	-----	-----
NW	1915	225	.38	184	17	.58	164	5	.16	123	-----	-----	-----	-----	-----	-----
	1919	276	.56	172	69	.36	150	15	.40	149	8	.40	216	-----	-----	-----
	1920	205	.33	159	62	.33	178	20	.57	159	21	.66	168	5	0.85	166
Mean	-----	706	.43	172	148	.36	163	40	.45	154	29	.56	176	5	.85	166
NNW	1915	192	.32	211	12	.92	234	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1919	300	.33	182	107	.37	180	3	.10	40	6	.53	177	-----	-----	-----
	1920	191	.25	160	29	.21	208	6	.65	181	2	.36	147	-----	-----	-----
Mean	-----	683	.29	183	148	.36	193	9	.41	178	8	.48	172	-----	-----	-----

In discussing Table 20 it will be convenient, as with the similar tables for the other light vessels, to designate the wind velocities of the various columns by their approximate means rather than by the two limiting values. Thus, winds of 10 to 19 miles per hour will be spoken of as 15-mile winds, 20 to 29-mile winds as 25-mile winds, etc.

A direct average of the mean velocities for each wind direction in Table 20 gives for the 15-mile wind a current of 0.38 knot; 25-mile wind, 0.77 knot; 35-mile wind, 0.97 knot; 45-mile wind, 1.04 knots; and 55-mile wind, 1.32 knots. These values give a relation of current to wind of 2.9, 3.6, 3.2, 2.7, and 2.8 per cent, respectively, or an average relation of 3 per cent. This is considerably larger than that found at the other light vessels.

In Table 20 the current velocities associated with northerly winds are generally less than those associated with southerly winds of the same strength. If we take the average current associated with northerly winds from east-northeast to west-northwest, the results are as follows: 15-mile wind, 0.30 knot; 25-mile wind, 0.36 knot; 35-mile wind, 0.44 knot; 45-mile wind, 0.55 knot; 55-mile wind, 0.68 knot. For the southerly winds from east-southeast to west-southwest the corresponding results are, respectively, 0.44, 0.90, 1.27, 1.44, and 1.64 knots. On the average, therefore, the southerly winds bring about currents having velocities more than twice as great as those brought about by northerly winds.

The direction of the wind current is, from Table 20, generally to the right of the wind except for winds from the southwest quadrant, for which the direction of the current is to the left of the wind. For the four quadrants the deviation of the current from the direction of the wind is, in round numbers, as follows: With winds from north to east, 15° to the right; with winds from east to south, 20° to the right; with winds from south to west, 35° to the left; with winds from west to north, 10° to the right.

VIII. OBSERVATIONS ON SWIFTSURE BANK LIGHT VESSEL

LOCATION AND LENGTH OF SERIES

Swiftsure Bank Light Vessel is stationed off the entrance to the Strait of Juan de Fuca, in latitude 48° 31′ 44″ N., longitude 125° 00′ 00″ W. It is anchored in 26 fathoms of water, the nearest coast being that of Vancouver Island, about 10 miles northeasterly, while Cape Flattery lies about 15 miles southeast. The location of the light vessel is shown in Figure 20.

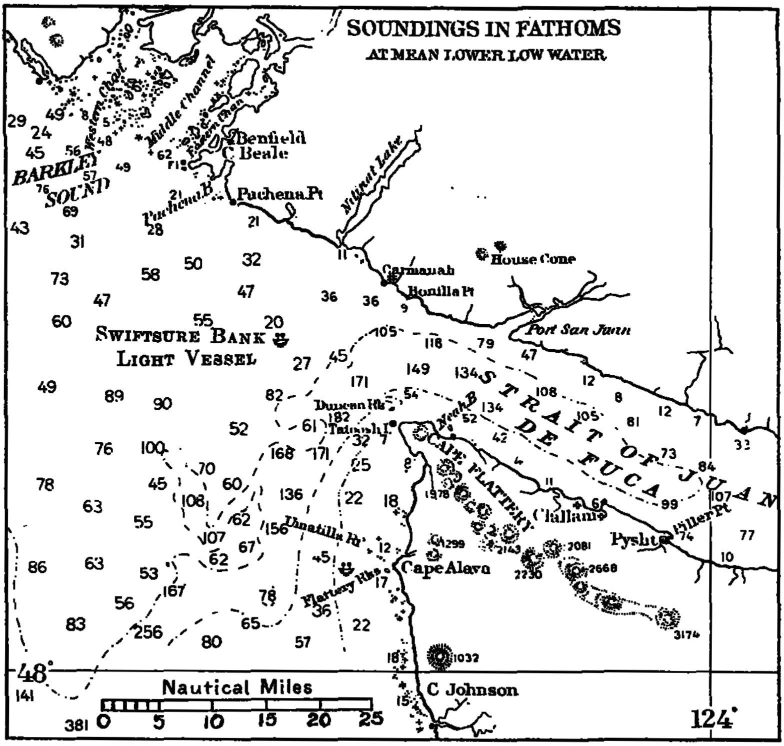

FIG. 20.—Location of Swiftsure Bank Light Vessel

For Swiftsure Bank Light Vessel there are at hand the results of two series of current observations made aboard the light vessel. The first comprises six months, extending from April 22 to October 31, 1915. The second series covers the period from December 6, 1918, to December 31, 1920. Throughout the entire period, with the exception of the last month, the current observations were made by means of a log line graduated for a run of 28 seconds, which interval was determined by means of a sand glass.

TIDAL CURRENT

The tidal current at Swiftsure Bank Light Vessel is decidedly rotary in character, with a minimum velocity of a third of a knot and a velocity at strength of three-quarters of a knot, on the average.

The velocities and directions of the tidal current for the years 1915, 1919, and 1920 are given in Table 21.

For the years 1919 and 1920 the values given in the table were derived from tabulations for the months of February, May, August, and November. For 1915 the data given were derived from tabulations for the three months May, August, and October. The same procedure was followed here as with the observations on the other light vessels. The current observed each hour was resolved into magnetic north-and-south and east-and-west components, and these resolved hourly values were then tabulated with reference to the times of high and low water at Astoria, Oreg., in periods of 29 days, beginning with the first of the month. The resulting mean hourly values of the current for each month tabulated were then plotted, as was also the average nontidal current for the month, and from this plotting the tidal current freed from the nontidal current was obtained for each tidal hour. In the table HH and LL refer, respectively, to the times of higher high water and lower low water at Astoria, Oreg., while H and L refer to the times of lower high water and higher low water. The velocities are given in knots and the directions are true, reckoned from north as 0°; east, 90°; south, 180°; west, 270°. The mean values in the last two columns of the table were derived by resolving the corresponding values for each year and adding algebraically, 1915 receiving but three-quarters the weight of 1919 or 1920.

TABLE 21.—*Mean tidal current, Swiftsure Bank Light Vessel*

[Referred to time of tide at Astoria, Oreg.]

Tidal hour	1915		1919		1920		Mean	
	Velocity	Direction	Velocity	Direction	Velocity	Direction	Velocity	Direction
	Knots	*Degrees*	*Knots*	*Degrees*	*Knots*	*Degrees*	*Knots*	*Degrees*
HH−3	0.63	319	0.39	323	0.46	328	0.48	324
HH−2	.41	344	.27	6	.43	360	.36	357
HH−1	.33	23	.32	60	.34	54	.32	47
HH	.38	73	.38	84	.40	91	.38	84
HH+1	.51	102	.46	106	.50	115	.48	108
HH+2	.41	127	.45	122	.49	138	.42	133
HH+3	.42	173	.33	171	.42	200	.38	171
LL−3	.44	225	.41	237	.39	214	.40	226
LL−2	.60	256	.54	266	.55	260	.56	261
LL−1	.80	278	.76	287	.67	280	.73	282
LL	.90	293	.85	299	.75	292	.82	295
LL+1	.78	306	.76	315	.73	308	.76	311
LL+2	.56	336	.54	340	.57	332	.55	336
LL+3	.44	31	.38	23	.43	16	.41	23
H−2	.65	70	.44	60	.49	53	.52	61
H−1	.84	89	.59	90	.64	87	.68	89
H	1.00	96	.73	108	.80	103	.82	102
H+1	1.09	114	.82	120	.87	118	.90	117
H+2	.97	129	.80	129	.90	129	.85	130
L−2	.59	174	.50	177	.55	176	.54	176
L−1	.47	214	.37	223	.44	231	.42	224
L	.54	264	.50	264	.56	263	.53	264
L+1	.65	294	.57	295	.64	286	.62	292
L+2	.76	307	.54	314	.61	311	.62	311

Diagrammatically, the mean tidal current at Swiftsure Bank Light Vessel is shown in Figure 21. This is based on the data of the last two columns of Table 21. The direction of rotation is seen to be clockwise, strength of flood setting southeasterly and coming about one and one-half hours after high water at Astoria, while strength of ebb sets northwesterly and comes from a little after low water to one and one-half hours after low water. The diagram shows that the current here has considerable diurnal inequality, the greater flood coming with lower high water at Astoria and the greater ebb with lower low water.

Since Figure 21, which represents the average tidal current at Swiftsure Bank Light Vessel, exhibits considerable diurnal inequality, it follows that this feature changes considerably throughout

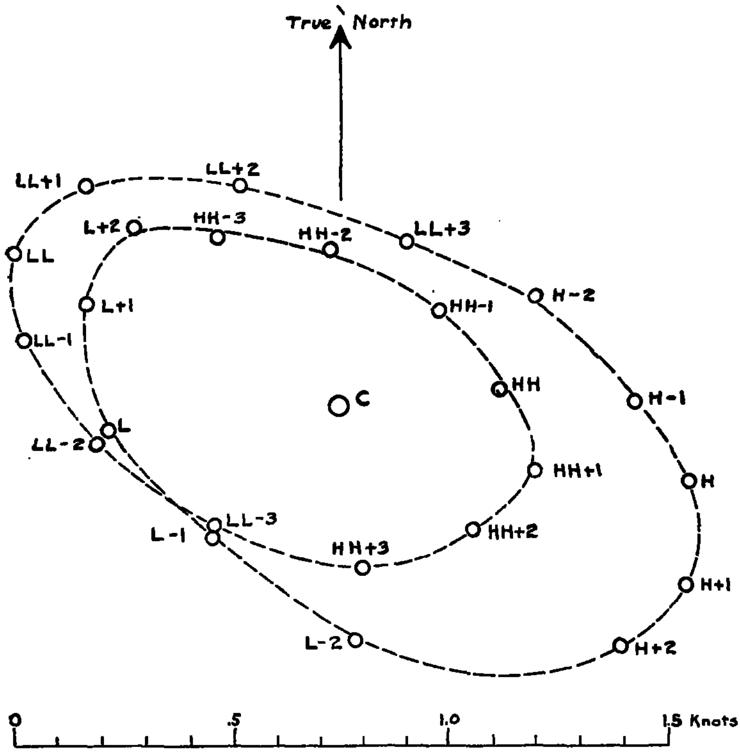

FIG. 21.—Mean tidal current curve, Swiftsure Bank Light Vessel

the month in response to changes in the moon's declination. Figures 22 and 23 represent, respectively, the current curves at this light vessel at the times of the moon's least and greatest semimonthly declination. These figures are derived from a tabulation of the observations for 1919, groups of three days being used, namely, the currents on the day of the moon's equatorial passage (or maximum north or south declination) and the two following days. This, in effect, assumes a diurnal age of one day.

Figure 22 shows that when the moon's declination is close to zero the diurnal inequality practically disappears. The strength of the current then has a velocity, on the average, of 0.7 knot and the minimum current a velocity of 0.35 knot. When the moon is near the Tropics—that is, when its declination is considerable—Figure

23 shows that the difference in morning and afternoon currents at Swiftsure Bank Light Vessel is considerable. The greater current, which is associated with lower low, lower high, and part of higher low water at Astoria, has a period of approximately 15 hours, while the lesser current, which is associated with higher high and a part of higher low water at Astoria, has a period of but 10 hours. The velocity at strength for the greater current is about 1 knot for the flood and 0.85 knot for the ebb, while for the lesser current the strength of flood is but 0.25 knot; the difference in strength of current for the greater and lesser ebb current is but little, 0.85 knot against 0.60 knot.

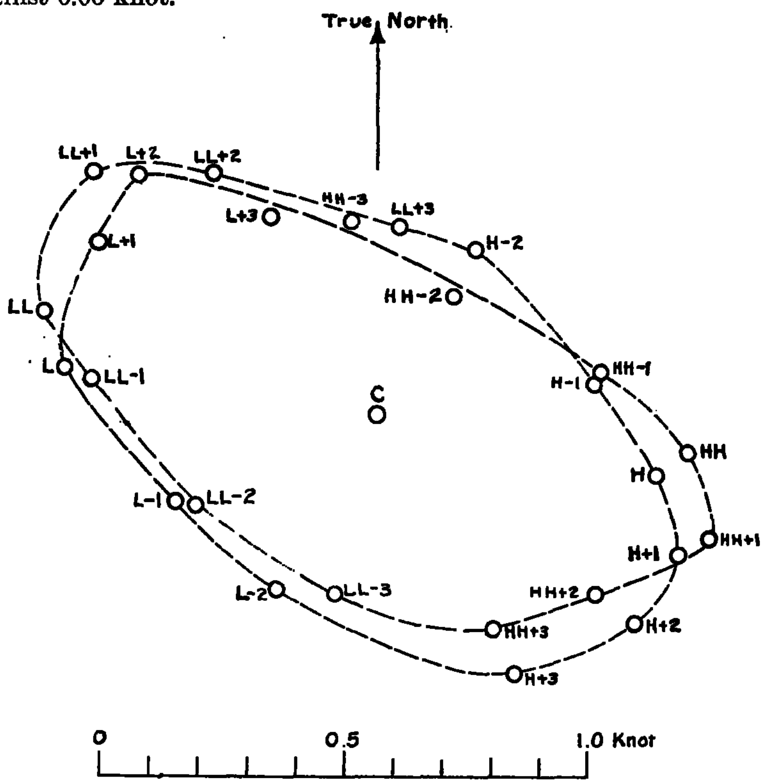

FIG. 22.—Equatorial tidal current curve, Swiftsure Bank Light Vessel

The tidal current at Swiftsure Bank Light Vessel is frequently masked by nontidal currents with a northwesterly set which in the winter may have a monthly average velocity of more than half a knot.

NONTIDAL CURRENT

The nontidal current at Swiftsure Bank Light Vessel for each month of the period of observations is given in Table 22. The values given were derived in the same manner as for the other light vessels. For each month the nontidal current was derived by summing algebraically the resolved values (resolved into north-and-south and east-and-west components) of the observed hourly velocities and directions of the current. Unless otherwise noted, the observations used for each month were the first 29 days, except for the month of February, when the last day of January was included to complete a 29-day group. The velocities in the table are in knots and the directions are true, reckoned clockwise from north as zero.

It is obvious that the fresh water from the territory that the Strait of Juan de Fuca drains must be a large factor in the nontidal current at Swiftsure Bank Light Vessel. Table 22 proves this to be the case, for the direction of the current is seen to be westerly every month. For the entire period of the observations the nontidal current aver-

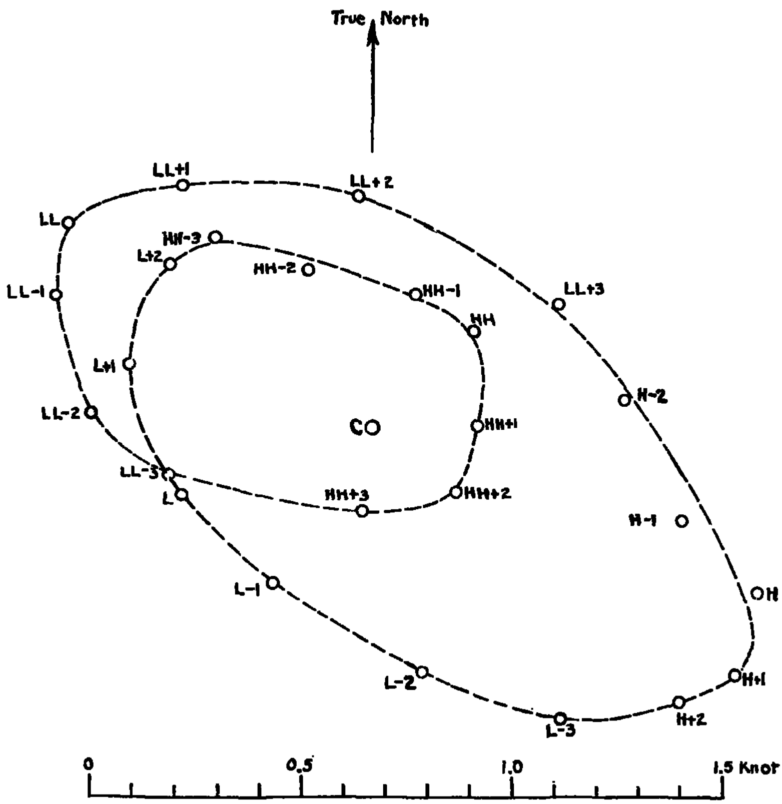

FIG. 23.—Tropic tidal current curve, Swiftsure Bank Light Vessel

aged 0.47 knot, setting 316°, or almost due northwest, and for every month of this period the nontidal current averaged northwesterly with the single exception of June, 1915, for which month Table 22 gives a direction 7° south of west.

The velocity of the nontidal current appears to be greatest during the fall and winter months and least during spring and summer. This variation can not be ascribed to changes in the volume of the drainage waters setting seawards, for the fresh-water discharge of the streams draining into the Strait of Juan de Fuca is least during the fall months. It appears to be due, however, to the winds which here are prevailingly from the east during fall and winter and from the west or southwest during spring and summer.

TABLE 22.—*Nontidal current, Swiftsure Bank Light Vessel; average velocity and direction*

Month	1915		1918		1919		1920	
	Velocity	Direction	Velocity	Direction	Velocity	Direction	Velocity	Direction
	Knots	*Degrees*	*Knots*	*Degrees*	*Knots*	*Degrees*	*Knots*	*Degrees*
January	-----	-----	-----	-----	0. 68	326	0. 64	313
February	-----	-----	-----	-----	. 51	327	. 47	[1] 310
March	-----	-----	-----	-----	. 53	331	. 20	332
April	-----	-----	-----	-----	. 34	323	. 15	279
May	0. 66	322	-----	-----	. 09	282	. 37	314
June	. 32	263	-----	-----	. 37	284	. 26	303
July	. 55	301	-----	-----	. 53	301	. 56	307
August	. 65	306	-----	-----	. 47	322	. 51	309
September	. 51	318	-----	-----	. 56	318	. 74	328
October	. 67	328	-----	-----	. 46	327	. 50	333
November	-----	-----	-----	-----	. 46	325	. 43	[2] 299
December	-----	-----	0. 46	[3] 348	. 53	308	. 84	313
Mean	. 53	311	-----	-----	. 45	318	. 46	314

[1] For February, 1920, the data given are based on 23 days of observations, from the 1st to the 29th, with a 6-day break from 15th to 20th.
[2] For November, 1920, the data given are based on 26 days of observations, from the 1st to the 26th.
[3] For December, 1918, the data given are based on 26 days of observations, from Dec. 6 to 21 and Dec. 26 to Jan. 4.

WIND CURRENT

In Table 23 are given the results of a tabulation of the currents at Swiftsure Bank Light Vessel accompanying winds from 16 directions. In this tabulation the resolved velocities of the current were used, and the tabulation was made in accordance with the method used for the observations on the other light vessels and which was outlined in Section III, under "Tabulation of light vessel observations," and in Section IV under "Wind current." In this table the wind velocities are given in miles per hour, the current velocities in knots, and the direction of the current in degrees reckoned clockwise from north as zero.

TABLE 23.—*Wind currents, Swiftsure Bank Light Vessel*

Winds rom—	Year	Wind 10-19			Wind 20-29			Wind 30-39			Wind 40-49			Wind 50-59		
		Current			Current			Current			Current			Current		
		No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.
			Knots	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*
N	1915	4	0. 54	237	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1918	1	1. 00	232	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1919	2	1. 84	326	3	0. 67	176	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1920	6	. 12	148	1	1. 20	88	-----	-----	-----	-----	-----	-----	-----	-----	-----
Mean	-----	13	. 33	279	4	. 60	146	-----	-----	-----	-----	-----	-----	-----	-----	-----
NNE	1915	1	1. 20	293	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1918	3	. 73	295	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1919	52	. 42	266	5	. 58	154	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1920	21	. 69	304	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Mean	-----	77	. 49	. 282	5	. 58	154	-----	-----	-----	-----	-----	-----	-----	-----	-----

TABLE 23.—*Wind currents, Swiftsure Bank Light Vessel*—Continued

Wind from—	Year	Wind 10-19			Wind 20-29			Wind 30-39			Wind 40-49			Wind 50-59		
		Current			Current			Current			Current			Current		
		No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.
			Knots	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*
NE	1919	42	0.78	281	10	0.21	175	6	0.52	127	-----	-----	-----	-----	-----	-----
	1920	23	.21	258	10	.34	265	4	1.19	261	-----	-----	-----	-----	-----	-----
Mean	-----	65	.57	278	20	.20	233	10	.34	220	-----	-----	-----	-----	-----	-----
ENE	1915	55	.23	318	2	.47	311	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1918	9	.75	304	-----	-----	-----	1	1.20	293	-----	-----	-----	-----	-----	-----
	1919	238	.65	295	54	.61	277	4	.75	256	-----	-----	-----	-----	-----	-----
	1920	192	.64	289	63	.86	289	5	.65	323	1	1.20	319	-----	-----	-----
Mean	-----	494	.60	294	119	.74	285	10	.64	291	1	1.20	319	-----	-----	-----
E	1915	60	1.01	299	31	.87	292	5	1.88	315	-----	-----	-----	-----	-----	-----
	1918	12	.72	323	11	1.23	315	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1919	171	.64	302	77	.94	300	33	1.06	308	11	1.17	299	-----	-----	-----
	1920	197	.55	297	148	.89	310	36	.87	306	27	1.04	295	-----	-----	-----
Mean	-----	440	.65	300	267	.91	305	74	1.02	308	38	1.08	296	-----	-----	-----
ESE	1915	201	.80	314	37	1.14	256	1	2.00	293	-----	-----	-----	-----	-----	-----
	1918	46	.77	323	27	1.14	309	4	.82	308	6	1.20	298	-----	-----	-----
	1919	528	.66	314	307	.88	310	50	.81	322	33	.98	318	-----	-----	-----
	1920	363	.65	317	224	.85	313	88	.91	309	65	1.09	309	-----	-----	-----
Mean	-----	1,138	.69	315	595	.87	307	143	.87	313	104	1.05	311	-----	-----	-----
SE	1915	50	1.08	324	3	.85	318	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1918	3	.97	319	15	.97	338	1	1.21	302	3	1.73	289	-----	-----	-----
	1919	52	.64	332	56	.54	338	14	.78	332	8	.64	339	-----	-----	-----
	1920	61	.82	336	78	.89	325	18	.93	327	12	1.19	320	-----	-----	-----
Mean	-----	166	.84	330	152	.76	330	33	.87	328	23	1.03	318	-----	-----	-----
SSE	1915	239	.74	321	64	.92	325	17	.93	358	2	1.42	373	-----	-----	-----
	1918	10	1.02	338	8	.90	323	19	1.21	327	7	.53	353	-----	-----	-----
	1919	316	.62	333	166	.72	344	79	.84	350	74	.73	351	16	0.62	336
	1920	336	.58	341	183	.58	342	56	.86	350	38	.91	350	4	1.21	348
Mean	-----	901	.64	332	421	.69	339	171	.89	347	121	.78	352	20	.73	340
S	1915	41	.77	343	24	1.02	353	9	1.04	335	2	1.30	336	-----	-----	-----
	1918	6	.57	342	2	.95	383	3	.62	343	-----	-----	-----	2	.90	386
	1919	7	1.00	326	1	1.20	307	1	1.40	371	3	1.18	325	1	2.10	324
	1920	80	.43	355	50	.75	342	14	1.15	369	21	1.04	341	-----	-----	-----
Mean	-----	134	.56	347	77	.83	347	27	1.02	356	26	1.07	339	3	1.12	352
SSW	1915	68	.60	337	11	.66	345	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1918	22	.62	374	8	.55	375	2	.51	124	2	.72	35	-----	-----	-----
	1919	134	.47	360	53	.64	359	23	.70	366	8	.43	52	-----	-----	-----
	1920	138	.42	353	56	.47	371	10	.49	375	13	.77	3	1	1.70	339
Mean	-----	362	.48	353	128	.56	363	35	.59	371	23	.60	17	1	1.70	339
SW	1915	18	.69	344	3	.33	378	4	1.55	320	-----	-----	-----	-----	-----	-----
	1918	17	.55	409	5	.42	364	-----	-----	-----	1	1.60	383	-----	-----	-----
	1919	30	.53	345	18	.54	360	6	.53	334	3	.85	335	-----	-----	-----
	1920	59	.38	323	25	.63	330	9	.55	314	3	.48	357	-----	-----	-----
Mean	-----	124	.43	345	51	.54	344	19	.75	321	7	.75	354	-----	-----	-----
WSW	1915	94	.41	310	9	.58	346	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1918	8	.34	392	9	.69	414	2	1.48	407	2	.87	82	-----	-----	-----
	1919	180	.30	338	52	.58	324	17	.20	346	5	.20	137	-----	-----	-----
	1920	184	.32	333	57	.17	300	7	.50	112	14	.12	273	-----	-----	-----
Mean	-----	466	.30	330	127	.35	330	26	.23	409	21	.04	119	-----	-----	-----
W	1915	61	.28	307	8	1.05	328	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1918	4	.47	320	3	.58	450	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1919	54	.36	335	23	.47	393	11	.37	317	3	.36	253	-----	-----	-----
	1920	112	.17	306	51	.28	356	10	.42	385	16	.27	111	-----	-----	-----
Mean	-----	231	.24	316	85	.36	364	21	.33	352	19	.19	122	-----	-----	-----

TABLE 23.—*Wind currents, Swiftsure Bank Light Vessel*—Continued

Wind from—	Year	Wind 10-19			Wind 20-29			Wind 30-39			Wind 40-49			Wind 50-59		
		Current			Current			Current			Current			Current		
		No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.
			Knots	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*
WNW	1915	474	0.38	279	127	0.22	233	12	0.41	107	12	0.61	199	10	1.38	127
	1918	11	.46	313	6	.06	95	3	.76	252	-----	-----	-----	-----	-----	-----
	1919	637	.16	286	276	.12	212	37	.37	159	13	.23	280	1	1.10	266
	1920	436	.18	287	236	.16	207	70	.51	141	19	.40	176	11	.42	155
Mean	------	1,558	.25	282	645	.15	216	122	.43	145	44	.34	199	22	.79	137
NW	1915	35	.30	160	13	.73	338	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1918	-----	-----	-----	3	.94	171	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1919	62	.11	241	35	.40	249	3	.54	279	-----	-----	-----	-----	-----	-----
	1920	90	.40	292	42	.34	313	10	.82	165	7	.29	14	1	1.60	23
Mean	------	187	.19	270	93	.31	292	13	.59	176	7	.29	14	1	1.60	23
NNW	1915	13	.75	283	3	1.00	222	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1918	6	.70	224	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1919	66	.45	279	35	.47	253	-----	-----	-----	-----	-----	-----	-----	-----	-----
	1920	48	.22	280	16	.61	277	-----	-----	-----	-----	-----	-----	-----	-----	-----
Mean	------	133	.39	276	54	.52	258	-----	-----	-----	-----	-----	-----	-----	-----	-----

In discussing the wind currents at the other light vessels it was found convenient to designate the wind velocities in the various columns by a single value rather than by the two limiting values, use being made for this purpose of the approximate mean of the two limiting values. In discussing Table 23 this procedure will be followed, and winds of 10 to 19 miles per hour will be designated as 15-mile winds, winds of 20 to 29 miles per hour as 25-mile winds, etc.

Since the tidal current at Swiftsure Bank Light Vessel has a velocity at strength of very nearly 1 knot, it follows that such mean values in Table 23 as are based on few observations may be seriously in error. Omitting means based on less than 10 observations, a direct average of the mean velocities of the current for each wind direction gives for the 15-mile wind a current of 0.48 knot; 25-mile wind, 0.56 knot; 35-mile wind, 0.66 knot; 45-mile wind, 0.69 knot; 55-mile wind, 0.76 knot. These values give a relation of current velocity to wind velocity varying from 3.7 per cent for the 15-mile wind to 1.6 per cent for the 55-mile wind.

It is obvious, however, that the method used in deriving the values of the current in Table 23 does not eliminate the nontidal current due to fresh-water discharge or other nonwind agencies. A glance at the velocities of the current accompanying 15-mile winds shows a velocity of 0.84 knot for the southeast wind and a velocity of 0.19 knot for the northwest wind. Furthermore, for the 15-mile wind the accompanying current sets northwesterly for the various wind directions, evidencing the effect of the nontidal current, which from Table 22 was found to average for the period of observations 0.47 knot 316° true.

To derive the wind current at Swiftsure Bank Light Vessel freed from the effects of other currents it would be necessary to eliminate, first, the tidal current from the values given in Table 23. Then the resulting values would have to be freed from the current due to fresh-water discharge, and to obtain accurate values each daily group of wind-current data would have to be treated independently. Obviously, this would entail an enormous amount of computation and would necessitate extensive data relative to the fresh-water discharge. For a first approximation, however, it may be assumed that in any group of observations numbering 10 or more the tidal current will be very nearly eliminated and that it will be sufficient to subtract the average nontidal current from the mean values in Table 23. The resulting values determined graphically are given in Table 24. Results based on less than 10 observations have been omitted.

TABLE 24.—*Wind currents, Swiftsure Bank Light Vessel, freed from average nontidal current*

Wind from—	Wind 10-19			Wind 20-29			Wind 30-39			Wind 40-49			Wind 50-59		
	Current			Current			Current			Current			Current		
	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.	No. of obs.	Vel.	Dir.
		Knots	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*		*Knots*	*Deg.*
N	13	0.29	180												
NNE	77	.28	213												
NE	65	.35	223	20	0.49	160	10	0.61	170						
ENE	494	.24	247	119	.40	252	10	.29	248						
E	440	.24	267	267	.47	294	74	.57	301	38	0.67	282			
ESE	1,138	.22	313	595	.42	297	143	.42	310	104	.59	307			
SE	166	.41	346	152	.34	350	33	.43	341	23	.57	320			
SSE	901	.24	6	421	.33	12	171	.55	13	124	.50	26	20	0.37	12
S	134	.29	44	77	.52	19	27	.73	20	26	.67	357			
SSW	362	.30	18	128	.42	26	35	.50	33	23	.55	39			
SW	124	.23	70	51	.26	44	19	.29	329						
WSW	466	.20	113	127	.16	102	26	.52	110	21	.51	134			
W	231	.23	136	85	.35	86	21	.28	92	19	.65	132			
WNW	1,558	.30	164	645	.51	152	122	.90	140	44	.69	162	22	1.26	137
NW	187	.36	158	93	.23	170	13	1.00	158						
NNW	133	.31	192	54	.48	202									

In Table 24, with the exception of the 55-mile wind, the velocities of the current for any given wind velocity show much less variation than the corresponding velocities in Table 23. The average current velocities from the data of Table 24 are 0.28 knot for the 15-mile wind, 0.38 knot for the 25-mile wind, 0.55 knot for the 35-mile wind, 0.60 knot for the 45-mile wind, and 0.82 knot for the 55-mile wind. These values give the current a velocity which, expressed as a percentage of the wind velocity is, respectively, 2.1, 1.8, 1.8, 1.5, and 1.7 per cent, or an average of 1.8 per cent.

The directions of the current in Table 24 are generally to the right of the winds with which they are associated. For the four quadrants the deviation of the current from the direction of the wind is, on the average, as follows: With winds from the northeast quadrant, 8° to the left; with winds from the southeast quadrant, 24° to the right; with winds from the southwest quadrant, 16° to the right; with winds from the northwest quadrant, 32° to the right.

IX. COMPARISON OF RESULTS

TIDAL CURRENT

The tidal current at each of the five light vessels on the Pacific coast may be regarded as fairly well determined. While under the conditions obtaining the methods and instruments used were such as to make any one individual observation subject to a relatively large probable error, the large number of observations used in determining the tidal current tend to reduce the probable error in the result very materially.

At each of the light vessels the tidal current was found to be more or less rotary in character, the direction of rotation being in every case clockwise. At San Francisco, Columbia River, and Swiftsure Bank Light Vessels the tidal current was more decidedly rotary than at Blunts Reef and Umatilla Reef Light Vessels. The latter two light vessels are stationed about 4 miles from the coast, while the former are very nearly 10 miles from the coast. Along the Pacific coast of the United States, therefore, from 5 to 10 miles offshore, the tidal current is decidedly rotary in character, the direction of the rotation being clockwise.

All along this coast the coastal tidal current exhibits very considerable diurnal inequality, the greater flood current being associated generally with lower high water along the coast, while the greater ebb is generally associated with lower low water. The direction of the tidal current at time of strength of flood or ebb is influenced by the location of the light vessels with reference to inland tidal waters, the current at strength of flood setting toward the inland body of water and at strength of ebb away from it. The velocity of the tidal current at strength is less than half a knot, except at Swiftsure Bank Light Vessel, where it averages three-quarters of a knot.

NONTIDAL CURRENT

Since the current observations on the Pacific coast light vessels were made with a pole submerged 14 feet, the tabular values of the nontidal current for any period represent the average resultant current due to wind, fresh-water run-off, and other nontidal causes during this period as affecting the surface waters to a depth of 14 feet. For the period of observations, which covers parts of the years 1915, 1916, 1918, and all of 1919 and 1920, the nontidal current averaged 0.11 knot, 304°, at San Francisco Light Vessel; 0.12 knot, 236°, at Blunts Reef Light Vessel; 0.35 knot, 253°, at Columbia River Light Vessel; 0.17 knot, 353°, at Umatilla Reef Light Vessel; and 0.47 knot, 316°, at Swiftsure Bank Light Vessel.

The relatively large velocities of the nontidal current at Columbia River and Swiftsure Bank Light Vessels are obviously due to the fresh-water run-off from the large territories that the Columbia River and the Strait of Juan de Fuca drain. Where fresh water flow is not the principal factor, the average nontidal current along the Pacific coast of the United States may be taken as about 0.1 knot.

The direction of the average nontidal current varies from 236° at Blunts Reef Light Vessel to 353° at Umatilla Reef Light Vessel;

but for each of the light vessels it will be noted that the average nontidal current has a westerly component.

At San Francisco Light Vessel the prevailing winds are from the northwest quadrant. Hence the nontidal current here sets in a direction opposite to that of the wind, and is therefore to be ascribed to the fresh-water discharge through San Francisco Bay. At Blunts Reef Light Vessel the prevailing winds are northerly, which accounts for the southerly set of the nontidal current. At Columbia River Light Vessel the prevailing wind is from the northwest; the southwesterly set of the nontidal current is therefore the resultant effect of wind and fresh-water run-off from the Columbia River. At Umatilla Reef Light Vessel the prevailing winds are from the east and southeast in winter, while in the summer they are from the west and northwest. The nontidal current here shows a corresponding seasonal change in direction. The northerly set of the average nontidal current is therefore to be ascribed to the greater prevalence of southerly and southeasterly winds. At Swiftsure Bank Light Vessel the prevailing winds are westerly in summer and easterly in winter, but the drainage waters through the Strait of Juan de Fuca make the average nontidal current here set northwesterly. The seasonal change in the prevailing wind, however, is seen in the greater velocity of the nontidal current during the winter months.

VELOCITY OF WIND CURRENT

The determination of the current due to winds of given direction and velocity from the observations made on board the Pacific coast light vessels is a much more difficult problem than the determination of the tidal and nontidal currents. To enumerate some of the difficulties involved, it is to be recalled that the velocity of the wind was estimated by the observers on board the light vessel, and not observed instrumentally; that in associating the current observed at any instant with the wind blowing at that instant no account is taken of the effect of the velocity, direction, and duration of the wind prior to that instant; that the current as observed at any instant is the resultant not only of the wind current and of the tidal current, the latter of which varies continuously, but also of other variable nontidal currents due to fresh-water run-off, differences in density and temperature of the water, etc.; that in the method employed to obviate the enormous amount of time-consuming computation necessary to derive the wind current freed from the effects both of other nontidal currents and of the tidal current the elimination of these effects is imperfect, especially in the case of winds for which but few observations are at hand.

In the tables of wind currents for the various light vessels no tabulations are given for winds in excess of 59 miles per hour. With very strong winds, current observations become difficult to make and at times even dangerous, so that too few current observations with higher wind velocities are at hand to give trustworthy results.

In Table 25 are given the average velocities of the wind current corresponding to the various wind velocities as observed on board the five light vessels. These current velocities are derived from Tables 10, 13, 17, 20, and 24; but in deriving the results data based on less than 10 observations were omitted from the tables pertaining to San Francisco, Columbia River, Umatilla Reef, and Swiftsure Bank Light Vessels, while data based on less than 5 observations were omitted from Table 13, pertaining to Blunts Reef Light Vessel. In the case of San Francisco Light Vessel, the results for the southwest wind were not used in deriving the values in Table 25, for reasons given in discussing the wind currents in Section IV.

TABLE 25.—*Average velocity of wind-driven current*

Light vessel	Wind 10–19		Wind 20–29		Wind 30–39		Wind 40–49		Wind 50–59	
	Current		Current		Current		Current		Current	
	No. of obs.	Vel.	No. of obs.	Vel.	No. of obs.	Vel.	No. of obs.	Vel.	No. of obs.	Vel.
		Knots		*Knots*		*Knots*		*Knots*		*Knots*
San Francisco	13,467	0.20	6,247	0.33	1,155	0.42	505	0.56	66	(0.76)
Blunts Reef	9,786	.31	6,471	.45	1,655	.62	969	.77	315	(.82)
Columbia River	11,171	.29	7,681	.50	1,761	.62	1,120	.74	114	(.84)
Umatilla Reef	6,897	.38	2,552	.70	799	.99	782	1.12	57	(1.19)
Swiftsure Bank	6,500	.28	2,837	.38	704	.55	422	.60	42	(.75)
Mean		.29		.47		.64		.76		.87

In discussing the above-mentioned tables, on the data of which Table 25 is based, it was noted that the velocity of the current corresponding to a given wind velocity varied somewhat with the direction of the wind. Obviously, therefore, the average velocities of the current for each of the light vessels in Table 25 are comparable only if these averages for each wind-velocity group are based on data for corresponding wind directions. But a glance at the tables of wind currents for the various light vessels shows that it is only for the first wind-velocity group (winds 10 to 19 miles per hour) that there are observations for each wind direction. With the higher wind-velocity groups the number of directions for which there are sufficient observations decrease rapidly.

To derive comparable values in Table 25, the following procedure was employed in computing the average velocities at each of the light vessels. For the first wind-velocity group (10 to 19 miles per hour) the average velocity of the current was determined directly, since there were sufficient observations for each of the 16 wind directions. For the second wind-velocity group (20 to 29 miles per hour) an average velocity of the current was derived from the data for all wind directions for which there were sufficient observations (not less than 5 observations for Blunts Reef Light Vessel and not less than 10 for the other light vessels). This velocity was then corrected by a factor the numerator of which was the average velocity for the 10 to 19 mile wind-velocity group, and the denominator the velocity derived by averaging in the 10 to 19 mile wind-velocity group the values for the wind directions corresponding to those used in deriving the uncorrected average velocity for the 20 to 29 mile winds. For the next wind-velocity group (30 to 39 miles per hour) the same procedure was followed, except that the correction factor was determined from both the 10 to 19 and 20 to 29 mile wind-velocity groups.

In other words, the correction factor for any wind-velocity group was based on all wind-velocity groups to the left.

It is to be observed, however, that for each of the five light vessels the correction factor obtained as outlined above was unity, or so very close to it for the 20 to 29, 30 to 39, and 40 to 49 mile wind-velocity groups that no changes in the velocity of the corresponding currents were necessary. For the 50 to 59-mile group, however, the correction factor differed appreciably from unity, and the corresponding values of the current given in Table 25 are inclosed in parentheses to indicate that the correction factor has been applied to reduce them to mean values.

The observers on board the light vessels generally estimated the velocity of the wind in terms of the Beaufort scale. The 10 to 19-mile wind-velocity group would thus include winds of force 2 and 3, the corresponding velocities in statute miles per hour being given as 13 and 18 miles, respectively. It is therefore sufficiently accurate to regard the current derived from the 10 to 19 wind-velocity group as pertaining to a 15-mile wind. Similarly, the 20 to 29, 30 to 39, 40 to 49, and 50 to 59-mile wind-velocity groups may be regarded as constituting, respectively, data pertaining to 25, 35, 45, and 55-mile winds.

The mean velocities of the current in Table 25, expressed in terms of wind velocity, give for the various wind-velocity groups the following relations: 2.22 per cent for the 15-mile wind; 2.16 per cent for the 25-mile wind, 2.10 per cent for the 35-mile wind, 1.94 per cent for the 45-mile wind, and 1.82 per cent for the 55-mile wind. It is of interest to note that these percentages show a steady decrease for increasing wind velocity. On the average, with winds from 10 to 59 miles per hour, the wind-driven current along the Pacific coast at a distance of 5 to 10 miles from shore is 2.05 per cent of the velocity of the wind, and since a knot is 1.15 statute miles per hour, the wind-driven current here in knots is 1.78 per cent of the wind velocity in miles per hour.

Table 25 gives for each of the five light vesesls the mean velocities for each of the wind-velocity groups, but in the sections devoted to the discussion of the observations on the individual light vessels it was found that the velocity of the current for any given wind velocity varies somewhat with the direction of the wind. In Table 26 are given the results derived by grouping the wind-current data for each of the light vessels in accordance with the direction of the wind. For the purpose in view the data are grouped into the four primary quadrants. The values given are based directly on Tables 10, 13, 17, 20, and 24, no correction factor being applied.

Table 26 indicates that altogether apart from the effects of currents due to other causes the greatest wind current comes with southeasterly winds at San Francisco Light Vessel, with southwesterly winds at Blunts Reef Light Vessel, with northwesterly winds at Columbia River Light Vessel, with southeasterly winds at Umatilla Reef Light Vessel, and with northerly winds at Swiftsure Bank Light Vessel. In general, these greatest currents are about 20 per cent greater than average current derived in Table 25. In this connection, however, it is to be borne in mind that the method used for freeing the wind current from the effects of other nontidal currents is only approximate.

TABLE 26.—*Average velocity of wind-driven current for winds from different quadrants*

Light vessel	Wind from—	Wind 10-19		Wind 20-29		Wind 30-39		Wind 40-49		Wind 50-59	
		Current		Current		Current		Current		Current	
		No. of obs.	Vel.	No. of obs.	Vel.	No. of obs.	Vel.	No. of obs.	Vel.	No. of obs.	Vel.
	Quadrant		*Knots*		*Knots*		*Knots*		*Knots*		*Knots*
San Francisco	NE	1,059	0.19	377	0.39	------	------	------	------	------	------
	SE	1,904	.28	666	.44	205	0.48	138	0.62	24	0.92
	SW	2,075	.27	339	.31	76	.35	43	.48	6	.77
	NW	8,429	.11	4,866	.34	874	.43	323	.56	36	.78
Blunts Reef	NE	4,560	.32	2,863	.51	435	.67	150	.80	22	.67
	SE	1,825	.29	1,480	.39	733	.64	595	.79	255	.93
	SW	677	.34	384	.53	96	.73	66	.84	16	1.09
	NW	2,724	.27	1,744	.38	391	.48	158	.65	22	.67
Columbia River	NE	2,363	.26	1,371	.41	225	.44	96	.66	------	------
	SE	2,606	.28	2,271	.53	578	.64	434	.67	49	1.21
	SW	2,370	.27	1,984	.47	630	.60	435	.72	50	1.12
	NW	3,832	.34	2,056	.59	327	.74	155	.85	15	.79
Umatilla Reef	NE	691	.33	174	.47	20	.49	19	.81	------	------
	SE	2,384	.46	1,288	.90	424	1.28	518	1.56	42	1.53
	SW	1,380	.42	540	.86	211	1.18	136	1.29	15	1.53
	NW	2,442	.30	550	.35	143	.47	109	.53	------	------
Swiftsure Bank	NE	862	.28	272	.45	57	.47	19	.67	------	------
	SE	2,503	.28	1,340	.40	398	.51	283	.58	20	.37
	SW	1,134	.25	390	.32	104	.45	66	.57	------	------
	NW	2,000	.31	834	.40	146	.82	54	.68	22	1.26

DIRECTION OF WIND CURRENT

The direction of the wind-driven current at each of the five light vessels on the Pacific coast was found to deviate from the direction of the wind, the magnitude and direction of this deviation depending on the direction of the wind. In Table 27 the deviation of the wind-driven current from the direction of the wind is given for each of the light vessels, the data being grouped under the four primary quadrants. In the columns headed "Deviation" the unmarked figures indicate a deviation to the right of the wind direction, while the figures prefixed with a minus sign (—) indicate a deviation to the left. The data of this table are derived from Tables 10, 13, 17, 20, and 24, values based on less than 10 observations being omitted in all cases with the exception of Blunts Reef Light Vessel, for which values based on less than five observations were omitted. It is to be recalled that Tables 10, 17, and 24 give the wind currents, respectively, at San Francisco, Columbia River, and Swiftsure Bank Light Vessels freed from the average nontidal current.

Excepting the results for Swiftsure Bank Light Vessel, Table 27 shows a deviation of the wind current to the right of the wind for winds from the northeast, southeast, and northwest quadrants and a deviation to the left for winds from the southwest quadrant. For the four light vessels the average deviation is 23° to the right for northeasterly, southeasterly, and northwesterly winds, while for southwesterly winds the average deviation is 24° to the left.

TABLE 27.—*Deviation of wind-driven current from direction of wind*

Light vessel	Wind from—	Wind 10-19		Wind 20-29		Wind 30-39		Wind 40-49		Wind 50-59	
		Current		Current		Current		Current		Current	
		No. of Obs.	Deviation	No. of Obs.	Deviation	No. of Obs.	Deviation	No. of Obs.	Deviation	No. of Obs.	Deviation
	Quadrant		*Deg.*		*Deg.*		*Deg.*		*Deg.*		*Deg*
San Francisco	NE	1,059	28	377	5	------	------	------	------	------	------
	SE	1,904	16	666	22	205	14	138	15	24	0
	SW	2,075	−43	339	0	76	−4	43	27	6	−12
	NW	8,429	34	4,866	30	874	23	323	9	36	−16
Blunts Reef	NE	4,560	16	2,863	0	435	8	150	8	22	14
	SE	1,825	6	1,480	3	733	11	595	10	255	9
	SW	677	−11	384	−23	96	−13	66	−19	16	−12
	NW	2,724	28	1,744	2	391	11	158	−4	22	14
Columbia River	NE	2,363	8	1,371	13	225	62	96	62	------	------
	SE	2,606	50	2,271	37	578	28	434	42	49	25
	SW	2,370	−6	1,984	−7	630	−9	435	−23	50	2
	NW	3,832	56	2,056	56	327	53	155	29	15	14
Umatilla Reef	NE	691	13	174	26	20	31	19	42	------	------
	SE	2,384	19	1,288	26	424	18	518	14	42	5
	SW	1,380	−37	540	−38	211	−39	136	−40	15	−10
	NW	2,442	21	550	−25	143	−43	109	7	------	------
Swiftsure Bank	NE	862	2	272	−20	57	−16	19	12	------	------
	SE	2,503	25	1,340	24	398	26	283	18	20	34
	SW	1,134	28	390	11	104	−3	66	26	------	------
	NW	2,000	33	834	33	146	20	54	28	22	25

The fact that the results for Swiftsure Bank Light Vessel differ from those at the other light vessels is undoubtedly due to difference in location with respect to the coast. Of the five light vessels all but Swiftsure Bank Light Vessel have the coast line to the eastward, while the latter has the coast line to the northward. The deviation of the wind-driven current from the direction of the wind, therefore, depends on the angle between wind direction and coastline.

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