EARTH'S ROTATIONAL FORCE AND NAVIGATION

by

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Nature continually demonstrates that the combined of the prolonged action of minute forces is capable of exerting tremendous energy and of performing prodigious tasks. With its fellows, the tiny drop of water, changed into vapor through man's intervention, or lifted into clouds by nature's forces, turns the wheels of modern civilization; in solid and liquid forms it rends asunder and levels the loftiest mountain range; and, again, the persistent force of friction applied to the surface of the sea by the lightest of winds, re-enforced by the deflective force of the earth's rotation, does its humble part in energizing the mighty circulatory systems of the oceans. These are but examples of the continuous display of nature's forces working through its atoms of energy. It is with this last manifestation that this paper has to deal — with the shifting of the masses of water of the oceans through the medium of wind-produced currents, deflected by the earth's rotation on its axis, and also with its effect on the determination by the mariner of his vessel's position.

Before the advent of the steam vessel, the actual effect of the wind on the vessel itself, that is, so-called leeway, undoubtedly had marked effect on the track of the sailing vessel and on the determination of the dead-reckoning position; on the high-powered, deep-draft vessel of today, however, the actual wind effect on the superstructure is comparatively insignificant, yet the modern dead-reckoning position is apparently affected by the wind, and with varying results. A study of wind-driven currents within recent years has furnished the key to a solution of the problem, at least in part. These studies indicate that a great part of the "leeway", for which allowance is made by the mariner, is in reality the effect of wind-driven local currents with, of course, some direct wind effect. From experience the navigator knew that the wind affected the dead-reckoning position of his vessel, but he was not aware that this effect was produced indirectly, to a large extent, by currents driven by this same wind. Yet it can be shown that, on account of the deflective force of the earth's rotation acting on wind-driven currents, the winds of the same velocity do have quite different effects from port and from starboard hands. To these apparent anomalies are due the uncertain factors in any attempted empirical corrections which are based on tabulations of results of daily sets and drifts, compared with existing wind and sea conditions.

Types of current. — Before considering in detail the direct effects of wind-driven local currents, it may be well to sketch briefly a description of the various types of currents since, like the tides which give rise to some of them, there are various types.

Tides and currents are intimately related phenomena, or, in fact, may be considered as two different phases of the same phenomenon, since, accompanying the vertical movement of the water caused by the tidal forces of moon and sun, a horizontal movement also takes place, giving rise to currents. In addition, however, to those currents caused by astronomical forces working through the tides, others are brought about by meteorological conditions, and by physical differences in sea water in different parts of the oceans. These astronomical forces, combined with topographical features, as in the case of the tides, and with meteorological and physical conditions, give rise to five types of currents:

1) The *rectilinear* or reversing type, illustrated by the currents in most inland bodies of water, such as the Hudson River, Chesapeake Bay, Delaware Bay, etc.

2) The so-called *hydraulic* type, illustrated by the currents in straits connecting two independently tided bodies of water; for example, the East River (New York), Deception Pass (Washington), and Seymour Narrows (British Columbia).

3) The *rotary* type, illustrated by the currents in the open ocean and along the sea coast.

4) The *permanent* currents comprising the main oceanic circulation, illustrated by the Gulf Stream of the Atlantic and the Kuroshio or Japanese current of the Pacific.

5) The *wind-driven* currents of a temporary nature, produced by the friction of local winds on the surface of the water.

The first three types (rectilinear, hydraulic, and rotary) are of tidal origin and are therefore periodic thus lending themselves to accurate prediction in advance; the last two are non-periodic and are due to meteorological conditions, to dominant winds, to variations in barometric pressures over the oceans, and to differences in temperatures and densities of the sea water in different parts of the oceans. Like the agents which bring them into being, they defy accurate advance predictions.

The first two types (rectilinear and hydraulic) are of interest to the mariner in inland waters only and data for their determination are predicted in advance and furnished in current tables published annually by the important maritime nations. The third type (rotary), while encountered at sea, especially on coastwise traffic, is generally of small velocity, and, since it is rotary in character, its effect becomes nullified through a complete tidal cycle of about twelve and a half hours. This third type, however, being also of tidal origin, lends itself to accurate advance prediction, and in some cases in which the velocity of this type is comparatively high, as for example those currents over the greater part of George's Bank, current roses are provided on the chart. From these data existing local current conditions can be determined by reference to a standard current station for which advance predictions are made.

The fourth type (permanent oceanic currents), while of vital interest to the mariner in areas where they are confined, as in the case of the Gulf Stream in the Straits of Florida and along the course of its impingement against the continental shelf, has generally little effect on position determination over the wide expanses of the oceans. In the open ocean these currents are comparatively weak and are at the whim of local winds; they may, therefore, be treated by the mariner in the same manner as the ordinary local wind-driven currents, which will be treated at length hereinafter.

While the general lines of these permanent currents of the main oceanic circulation are fairly well understood, they have received little systematic study of a quantitative nature through direct observations. Their sets and drifts have been mapped in a general way; but the principal information on which this mapping has been done is in general of a qualitative nature obtained from the record of the drift of bottles and of wrecks, and from the difference between the true and the dead-reckoning positions of vessels, the determination of which does not permit of a high degree of accuracy. In recent years, however, deep-seated ocean currents have been studied through the physical properties of the sea water; dynamic oceanography is now providing a method for mapping currents over extensive ocean areas through a knowledge of the temperature and salinity conditions obtained from observations at several known depths at stations systematically located over an ocean area.

Deflective force of the earth's rotation. — All these currents, however, are affected by the rotation of the earth; it is the intent of this paper to demonstrate the effect on the mariner's position of this deflective force. Any water particle in motion undergoes a deviation from a straight path because of this deflective force of the earth's rotation, towards the right in the Northern Hemisphere and towards the left in the Southern. This deflective force is directly proportional to the velocity, to the mass of the particle, and to the sine of the latitude, hence, is zero at the equator and of opposite direction in north and south latitudes.

From direct observations, as well as from theoretical considerations, this deflective force can be shown to exist and to have marked effect on both tides and currents. In the case of the tides in estuaries, it brings about a difference in range on the two shores (1). Its action is toward the right (Northern Hemisphere) in the direction of the path of progress of the water particles and a greater range is brought about on the right shore. The theoretical value, in feet, by which the ranges on the two shores differ, is represented approximately by the formula,

$$\frac{3vd \sin \Phi}{g},$$

in which v is the velocity of the water in knots, d the width of the body in nautical miles, Φ is the latitude, and g is the acceleration of gravity in feet per second (approximately 32.2).

(1) *For formula, see Special Publication No.* 111, *U. S. Coast and Geodetic Survey, "Tides and Currents in New York Harbor", page* 68, *Govt. Printing Office, Washington, D. C.,* 1925.

A comparison, for example, of the mean ranges of the tide at points directly opposite on the eastern and western shores of Delaware and Chesapeake bays shows an average mean range four-tenths of a foot greater on the eastern than on the western shore of Delaware Bay, and three-tenths of a foot greater on the eastern than on the western shore of Chesapeake Bay. The Bay of Fundy, because of its large range of tide, furnishes a more striking example of this deflective force; the average mean range on the eastern shore is five and three-tenths feet greater than directly opposite on the western.

This deflective force of the earth's rotation causes the direction of this tidal current (type 3) to take a rotary motion; its direction changes constantly throughout a tidal cycle in a rotary movement, clockwise in the Northern Hemisphere, at a rate of about 30° per hour. The varying velocities, when plotted on polar co-ordinate paper, approximate an elliptical shape illustrated by Fig. 1. This figure illustrates graphically the velocities and directions of the current at Nantucket Shoals Light Vessel referred to the time of tide at Boston; the lengths of the radiating hour lines denote velocity. It will be noted that the current is constantly changing direction from *H* (high water) through each hour to *L* (low water) and so on to *H* again; and that the velocities are such that a free curve drawn through the extremities of ordinates approximates an ellipse. While the size of the ellipse (velocity) varies throughout a lunar month with the varying phases and with the changing declination of the moon, the set of the currents is in general the same at any time of the month for the same tidal hour.

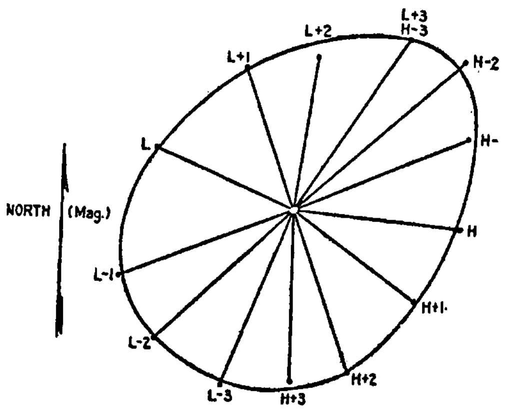

Fig. 1

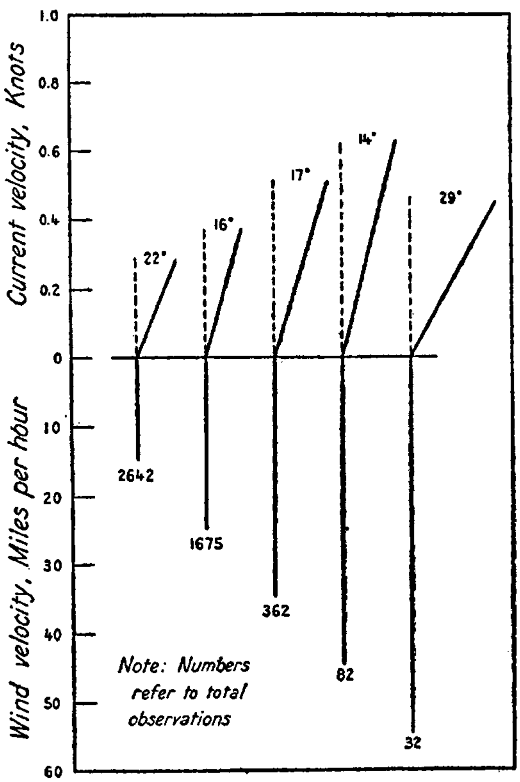

FIG. 2

It is well known that a wind continuing from one general direction for some time will give rise, through friction on the surface of the water, to a current, the velocity of which increases with an increase in the velocity of the wind, and the mariner has accepted that this wind-produced current sets in the same direction as the wind. The deflective force due to the earth's rotation, however, causes a marked deviation of the set of these currents along the coasts and in open ocean areas. In an ocean of infinite depth it can be shown (2) from theoretical considerations that a wind-driven current

(2) *On the Influence of the Earth's Rotation on Ocean Currents,* Arkiv für Mathematik, Astronomie, och Fysik, *Vol.* 2, *No* 11, 1905.

should be deflected on the surface 45° to the right of the wind direction in the Northern Hemisphere and 45° to the left in the Southern Hemisphere. Near the coast it is to be expected that this deflection should be modified to some extent by the configuration of the bottom and of the shore line. Investigations from comparatively long series of continuous current observations obtained during the past decade at different light vessels along the coast of the United States have verified this theory and brought out the fact, of importance to the mariner, that, contrary to his belief, a local wind creates a current along the coast, setting not in its own direction, but in a direction about 20° to the right of the wind. Figure 2 represents diagrammatically the results from a number of observations over a period of two years (1919-20) for a north-northwest wind at Blunt's Reef Light Vessel, on the Pacific coast of the United States, for velocities from 10 to 60 miles an hour. The deflections of the slanting lines from the vertical indicate the deflections of the resulting wind-driven currents to the right of the wind direction.

While a general law applies to the average current produced by any given wind velocity, it is obvious that along the coast line, the amount of deflection from the wind direction will depend upon the angle of impingement of this current against the coast; in some cases due to this angle the deflection is increased and in others decreased. It has been found, however, that the velocity of the current varies fairly proportionately with the wind velocity, and that it is 1.5 per cent to 2 per cent in knots of the wind velocity in miles per hour. To determine, therefore, the velocity of the current due to wind, an easily remembered approximate working rule is to multiply the velocity of the wind (in miles an hour), by 2 and point off two places; this will give the approximate velocity of the wind-produced current in knots. For example, to determine the current produced by a 50-mile wind, $50 \times 2 = 100$, and pointing off two places we have 1.00 or one knot.

The preceding statements regarding ocean currents have particular reference to coastwise currents; yet for wind-driven currents in the open ocean one may safely accept for practical purposes, and without additional discussior, the approximate velocity of 2 per cent of the wind velocity as the current drift.

As to the degree of deflection in the direction of wind-driven currents in the open ocean areas brought about by the force of the earth's rotation, limited quantitative data are available in addition to those furnished by the current observations made along the coasts from light vessels. An investigation of the relation of surface currents to wind direction has been made, however, for a part of the North Atlantic Ocean (latitude 47° to 53° N., longitude 10° to 36° W.) (3), and the results, shown in the form of a current rose, tend to verify the theory; a large number of these observed currents had a direction exactly 45° to the right of the wind direction.

The general oceanic circulation gives further evidence of the effect of the deflective force of the earth's rotation on the set of currents. The deep-seated ocean currents of both the Atlantic and the Pacific oceans each comprise two distinct and clearly defined major systems. In each ocean the circulation in the Northern Hemisphere is in a clockwise direction and in the Southern Hemisphere in a counter-clockwise direction. For example, the circulation of the Atlantic Ocean in the Northern Hemisphere comprises on the south the north equatorial current setting westward; on the west and north is the Gulf Stream setting northward and then eastward, and on the east the Canary current setting southward, to complete the circuit. And in the center of this mighty clockwise swirl is the comparatively stagnant Sargasso Sea, as though a giant finger had set this enormous basin of water awhirl, causing the flotsam and jetsam to collect at its center.

It has been sufficiently well demonstrated that 2 per cent of the wind velocity approximates the drift of wind-driven currents along the coast; this velocity may be accepted without serious error for similar currents in the open ocean areas. The set of the coastal currents is shown to be about 20° to the right (Northern Hemisphere) of the wind direction; from theoretical considerations the deflection is 45° to the right in an open ocean area of infinite depth. Considering, therefore, only these data, it would appear logical to accept a mean of the two, or 30° to 35°, as the set of wind-driven currents in the open ocean, except that the investigations of such currents in the North Atlantic, to which reference has been made, indicate that the actual deflection approaches nearer the theoretical. It would appear, therefore, that a 40° deflection may be accepted without serious error for open ocean areas.

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(3) "The Marine Observer", IV, 153.

The preceding values, which for practical purposes can be accepted for use in open ocean areas with plenty sea room, may be summarized as follows:

1) The drift of wind-driven currents in the open ocean approximates in knots 2 per cent of the wind velocity in miles per hour.

2) The set of wind-driven currents in open ocean areas is about 40° to the right of the wind direction in the Northern Hemisphere and 40° to the left in the Southern Hemisphere.

Effects on a vessel. — Accepting these assumptions, which are based on both theory and direct observations, the effects of wind-driven currents on the determination by the mariner of the dead-reckoning position of a vessel may be discussed in detail. Such a discussion may well be demonstrated by examples, in which the wind directions are assumed to be from both the starboard and port hands, and from various directions relative to the fore-and-aft line of the vessel, since the deflection from a straight path taken by these wind-produced currents causes them to exercise different effects when put in motion by winds from different hands relative to the vessel. In these examples, it is to be understood that the different illustrative cases are assumed to be in the Northern Hemisphere and, therefore, that the deflections are to the right of the wind direction; in the Southern Hemisphere they would, of course, be to the left. Fully to demonstrate these different effects, eight cases have been taken, illustrated by Figs. 3 to 6, inclusive.

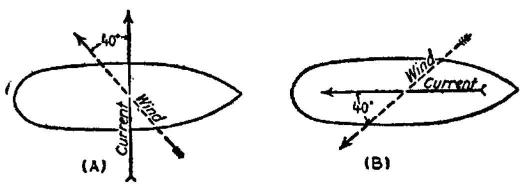

FIGURE 3

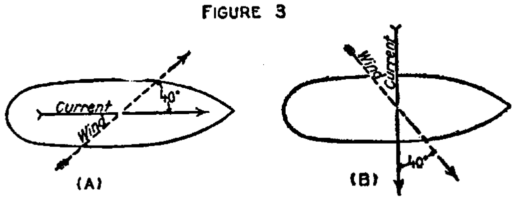

FIGURE 4

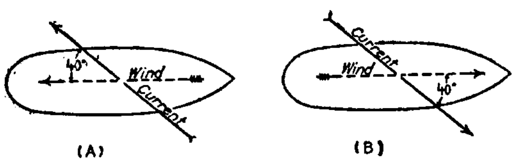

FIGURE 5

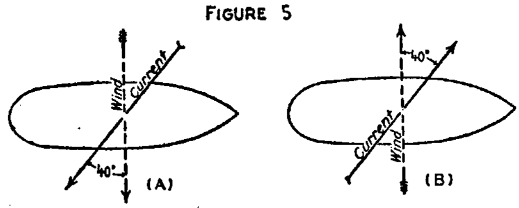

FIGURE 6

Figure 3*A* illustrates the current effect resulting from a wind 45° on the starboard bow. Assuming the wind velocity to be 35 miles an hour, the resulting current drift would be about 0.7 knot (2 per cent of the wind velocity), setting practically athwartship (40° to the right of the wind direction); and, unless taken into consideration by the mariner and an allowance made, the vessel's position at the end of a 24 hour period would be about 17 miles to port of the course laid down. In order to demonstrate the fact that a different effect accrues from a similar wind from the other hand, Fig. 3*B* illustrates the effect from a wind 45° on the port bow. Assuming the same wind velocity the resulting current drift would be 0.7 knot, but setting practically aft and directly against the vessel's progress. In this case, outwardly similar to the last one, the vessel's position at the end of a 24 hour period, however, would be very nearly on the course laid down, but about 17 miles short of her logged distance.

A wind 45° on the starboard quarter produces a current setting practically fair with the vessel's progress through the water (Fig. 4*A*); the logged distance, therefore, will be less than the actual distance made good over the ground. Fig. 4*B* illustrates a wind 45° on the port quarter; the resulting current effect in this case, however, is practically athwartship. But for the deflective force due to the earth's rotation, the resulting current effect in these two cases, apparently quite similar otherwise, would have been identical.

Fig. 5*A*, illustrating a wind from dead ahead, demonstrates that the resulting current sets about 40° across the starboard bow, while in Fig. 5*B*, with the wind dead astern, the resulting current sets about 40° on the port quarter.

With the wind on the port beam (Fig. 6*A*), the resulting current sets 40° on the port bow and, therefore, somewhat against the progress of the vessel over the ground. With the wind on the starboard beam (Fig. 6*B*), the resulting current sets 40° on the starboard quarter and, therefore, somewhat fair with the progress of the vessel over the ground.

It must be borne in mind that the effects of currents on the dead-reckoning positions, illustrated in Figs. 1-6, are wholly external to the vessel; that is, the whole mass of water, bearing the vessel, shifts its position in the ocean. This mass movement can, of course, be taken into account in the dead reckoning, either by regarding the current set and drift as a course and distance to be reckoned with, or, in order to follow more closely the track laid down, it can be allowed for by application of the graphic method of the "current rule" with which all mariners are familiar. In the two cases, however, illustrated by Figs. 4*A* and 4*B*, another problem arises due to the effects produced by action of the vessel itself. This additional source of error is brought about by the effect on the steering of the vessel, quite probable under the conditions illustrated by these two figures, with the wind on either quarter. This factor should be given consideration by the mariner, irrespective of the effects of the current as illustrated hereinbefore.

If the winds in these two cases are accompanied by a heavy quartering sea, the vessel tends to work to windward, especially to starboard, because of the effect on the steering brought about by the pounding of heavy seas on the quarter. A careful conning of the helmsman under these conditions generally will disclose that when off course, it is usually toward the side against which the following sea is directed. The resulting error is sometimes as much as two to three-tenths of a mile an hour off the course laid down, depending upon the force of the sea and somewhat upon the vessel.

In making allowance for this correction to the course steered, consideration should be given to the difference in effects of the sea from the starboard quarter and from the port quarter. If the sea is from the starboard quarter, the vessel will work to windward (starboard) the maximum amount, since the current, due to the starboard quartering wind, sets fair with the vessel's course (Fig. 4*A*) and therefore has no compensating effect. On the other hand, the working to windward from a quartering port sea will quite probably be compensated entirely by the effect of the wind-produced current, since the current, due to a port quartering wind, sets practically athwartship (Fig. 4*B*), in a direction opposite to that of the error due to the vessel's working to windward to the port hand. In making steering allowance for the two conditions to make good the course laid down, it is obvious, of course, that the resultant of the two forces must be considered.

The mariner should not expect complete agreement always in the application of the theories and the assumptions set forth in this paper; many factors are involved not possible of evaluation in the present state of oceanography. The comments are offered him as an indication of the possibilities in the application of the known and proven factors and as a stimulus to further study on his part toward the possible evaluation of others yet unknown or unproven. The author will appreciate comments from the mariner, based on actual trial at sea, either in proof or disproof of the theories set forth herein.

At sea, especially in coastwise navigation, constant vigilance on the part of the navigator is the price of safety; for at times wind-driven currents of considerable velocity precede the wind which cause them. The writer has not observed this current condition preceding the wind by more than four to six hours. Attention should be called to the fact that these abnormal conditions are rarely encountered; they are mentioned in order that the mariner may appreciate that remote unknown factors, not possible of evaluation, may at times affect his reckoning.