CHAPTER 9

TIDES AND TIDAL CURRENTS

ORIGINS OF TIDES

900. Introduction

Tides are the periodic motion of the waters of the sea due to changes in the attractive forces of the Moon and Sun upon the rotating Earth. Tides can either help or hinder a mariner. A high tide may provide enough depth to clear a bar, while a low tide may prevent entering or leaving a harbor. Tidal current may help progress or hinder it, may set the ship toward dangers or away from them. By understanding tides and making intelligent use of predictions published in tide and tidal current tables and descriptions in sailing directions, the navigator can plan an expeditious and safe passage through tidal waters.

901. Tide and Current

The rise and fall of tide is accompanied by horizontal movement of the water called tidal current. It is necessary to distinguish clearly between tide and tidal current, for the relation between them is complex and variable. For the sake of clarity mariners have adopted the following definitions: Tide is the vertical rise and fall of the water, and tidal current is the horizontal flow. The tide rises and falls, the tidal current floods and ebbs. The navigator is concerned with the amount and time of the tide, as it affects access to shallow ports. The navigator is concerned with the time, speed, and direction of the tidal current, as it will affect his ship's position, speed, and course.

Tides are superimposed on nontidal rising and falling water levels, caused by weather, seismic events, or other natural forces. Similarly, tidal currents are superimposed upon non-tidal currents such as normal river flows, floods, and freshets.

902. Causes of Tides

The principal tidal forces are generated by the Moon and Sun. The Moon is the main tide-generating body. Due to its greater distance, the Sun's effect is only 46 percent of the Moon's. Observed tides will differ considerably from the tides predicted by equilibrium theory since size, depth, and configuration of the basin or waterway, friction, land masses, inertia of water masses, Coriolis acceleration, and other factors are neglected in this theory. Nevertheless, equilibrium theory is sufficient to describe the magnitude and distribution of the main tide-generating forces across the surface of the Earth.

Newton's universal law of gravitation governs both the orbits of celestial bodies and the tide-generating forces which occur on them. The force of gravitational attraction between any two masses, m_1 and m_2, is given by:

$$F = \frac{G m_1 m_2}{d^2}$$

where d is the distance between the two masses, and G is a constant which depends upon the units employed. This law assumes that m_1 and m_2 are point masses. Newton was able to show that homogeneous spheres could be treated as point masses when determining their orbits.

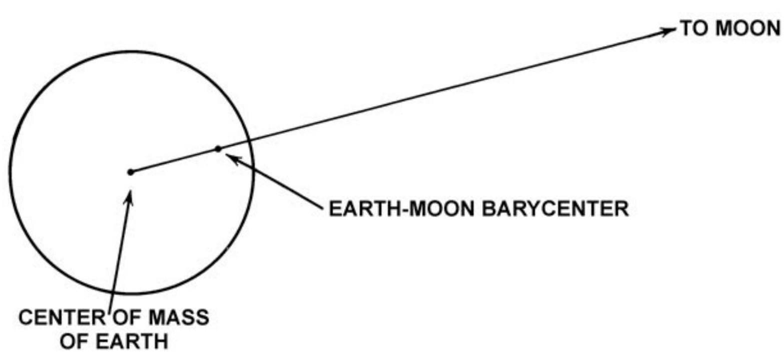

Figure 902a. Earth-Moon barycenter.

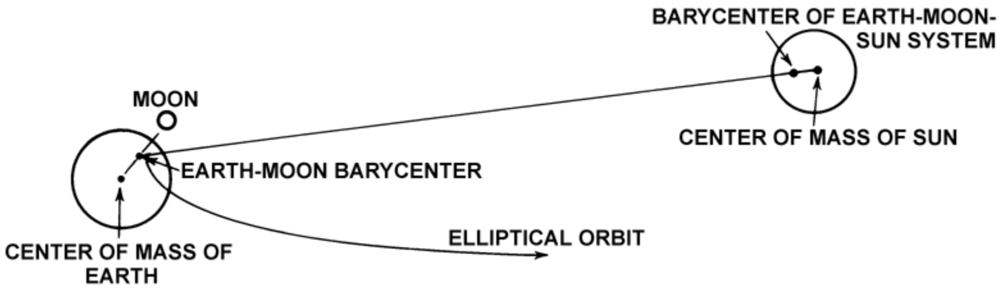

Figure 902b. Orbit of Earth-Moon barycenter (not to scale).

However, when computing differential gravitational forces, the actual dimensions of the masses must be taken into account.

Using the law of gravitation, it is found that the orbits of two point masses are conic sections about the **barycenter** of the two masses. If either one or both of the masses are homogeneous spheres instead of point masses, the orbits are the same as the orbits which would result if all of the mass of the sphere were concentrated at a point at the center of the sphere. In the case of the Earth-Moon system, both the Earth and the Moon describe elliptical orbits about their barycenter if both bodies are assumed to be homogeneous spheres and the gravitational forces of the Sun and other planets are neglected. The Earth-Moon barycenter is located 74/100 of the distance from the center of the Earth to its surface, along the line connecting the Earth's and Moon's centers. See Figure 902a.

Thus the center of mass of the Earth describes a very small ellipse about the Earth-Moon barycenter, while the center of mass of the Moon describes a much larger ellipse about the same barycenter. If the gravitational forces of the other bodies of the solar system are neglected, Newton's law of gravitation also predicts that the Earth-Moon barycenter will describe an orbit which is approximately elliptical about the barycenter of the Sun-Earth-Moon system. This barycentric point lies inside the Sun. See Figure 902b.

903. The Earth-Moon-Sun System

The fundamental tide-generating force on the Earth has two interactive but distinct components. The tide-generating forces are differential forces between the gravitational attraction of the bodies (Earth-Sun and Earth-Moon) and the centrifugal forces on the Earth produced by the Earth's orbit around the Sun and the Moon's orbit around the Earth. Newton's Law of Gravitation and his Second Law of Motion can be combined to develop formulations for the differential force at any point on the Earth, as the direction and magnitude are dependent on where you are on the Earth's surface. As a result of these differential forces, the tide generating forces F_{dm} (Moon) and F_{ds} (Sun) are inversely proportional to the cube of the distance between the bodies, where:

$$F_{dm} = \frac{GM_mR_e}{{d_m}^3}; \quad F_{ds} = \frac{GM_sR_e}{{d_s}^3}$$

where M_m is the mass of the Moon and M_s is the mass of the Sun, R_e is the radius of the Earth and d is the distance to the Moon or Sun. This explains why the tide-generating force of the Sun is only 46/100 of the tide-generating force of the Moon. Even though the Sun is much more massive, it is also much farther away.

Using Newton's second law of motion, we can calculate the differential forces generated by the Moon and the Sun affecting any point on the Earth. The easiest calculation is for the point directly below the Moon, known as the **sublunar point**, and the point on the Earth exactly opposite, known as the **antipode**. Similar calculations are done for the Sun.

If we assume that the entire surface of the Earth is covered with a uniform layer of water, the differential forces may be resolved into vectors perpendicular and parallel to the surface of the Earth to determine their effect. See Figure 903a.

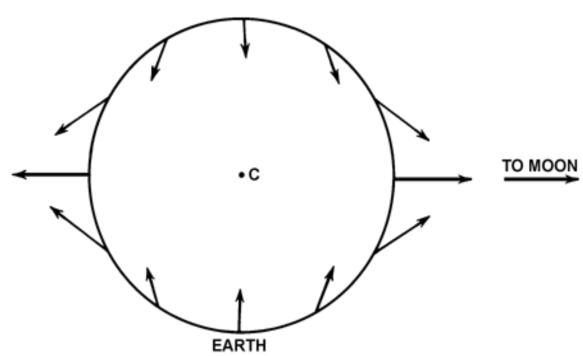

Figure 903a. Differential forces along a great circle connecting the sublunar point and antipode.

The perpendicular components change the mass on which they are acting, but do not contribute to the tidal effect. The horizontal components, parallel to the Earth's surface, have the effect of moving the water in a horizontal

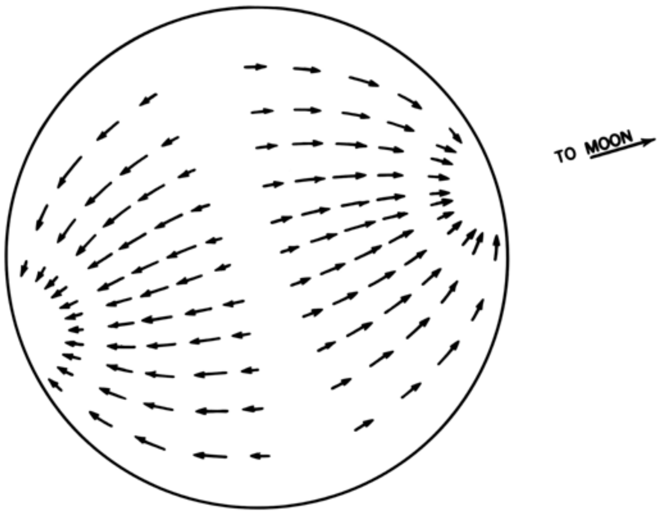

Figure 903b. Tractive forces across the surface of the Earth.

direction toward the sublunar and antipodal points until an equilibrium position is found. The *horizontal* components of the differential forces are the principal tide-generating forces. These are also called **tractive** forces. Tractive forces are zero at the sublunar and antipodal points and along the great circle halfway between these two points. Tractive forces are maximum along the small circles located 45° from the sublunar point and the antipode. Figure 903b shows the tractive forces across the surface of the Earth.

Equilibrium will be reached when a bulge of water has formed at the sublunar and antipodal points such that the tractive forces due to the Moon's differential gravitational forces on the mass of water covering the surface of the Earth are just balanced by the Earth's gravitational attraction (Figure 903c).

Now consider the effect of the rotation of the Earth. If the declination of the Moon is 0°, the bulges will lie on the equator. As the Earth rotates, an observer at the equator will note that the Moon transits approximately every 24 hours and 50 minutes. Since there are two bulges of water on the equator, one at the sublunar point and the other at the antipode, the observer will also see two high tides during this interval with one high tide occurring when the Moon is overhead and another high tide 12 hours 25 minutes later when the observer is at the antipode. He will also experience a low tide between each high tide. The theoretical range of these equilibrium tides at the equator will be less than 1 meter.

In theory, the heights of the two high tides should be equal at the equator. At points north or south of the equator, an observer would still experience two high and two low tides, but the heights of the high tides would not be as great as they are at the equator. The effects of the declination of the Moon are shown in Figure 903d, for three cases, A, B, and C.

A. When the Moon is on the plane of the equator, the forces are equal in magnitude at the two points on the same parallel of latitude and 180° apart in longitude.
B. When the Moon has north or south declination, the forces are unequal at such points and tend to cause an inequality in the two high waters and the two low waters each day.
C. Observers at points X, Y, and Z experience one high tide when the Moon is on their meridian, then another high tide 12 hours 25 minutes later when at X', Y', and Z'. The second high tide is the same at X' as at X. High tides at Y' and Z' are lower than high tides at Y and Z.

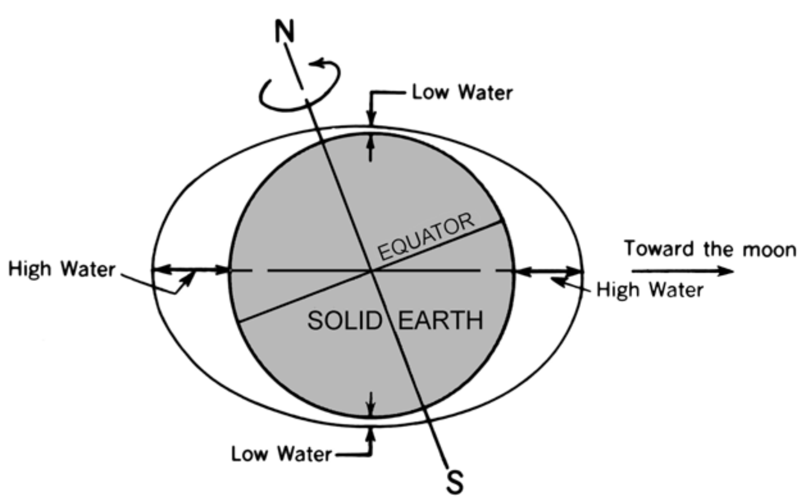

Figure 903c. Theoretical equilibrium configuration due to Moon's differential gravitational forces. One bulge of the water envelope is located at the sublunar point, the other bulge at the antipode.

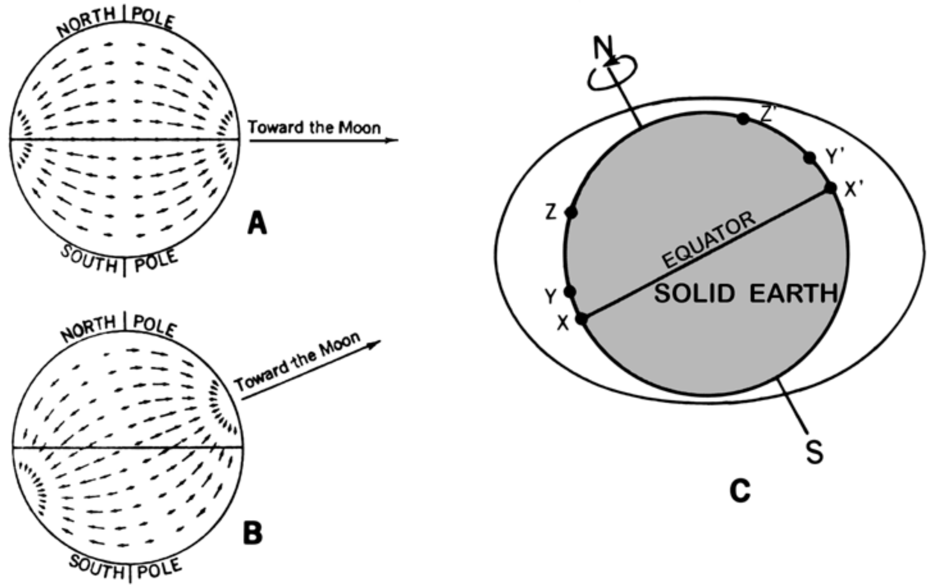

Figure 903d. Effects of the declination of the Moon.

The preceding discussion pertaining to the effects of the Moon is equally valid when discussing the effects of the Sun, taking into account that the magnitude of the solar effect is smaller. Hence, the tides will also vary according to the Sun's declination and its varying distance from the Earth. A second envelope of water representing the equilibrium tides due to the Sun would resemble the envelope shown in Figure 903c except that the heights of the high tides would be smaller, and the low tides correspondingly not as low. The theoretical tide at any place represents the combination of the effects of both the Moon and Sun.

FEATURES OF TIDES

904. General Features

At most places the tidal change occurs twice daily. The tide rises until it reaches a maximum height, called **high tide** or **high water**, and then falls to a minimum level called **low tide** or **low water**.

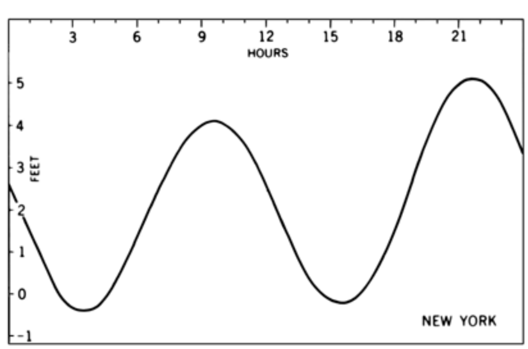

Figure 904. The rise and fall of the tide at New York, shown graphically.

The rate of rise and fall is not uniform. From low water, the tide begins to rise slowly at first, but at an increasing rate until it is about halfway to high water. The rate of rise then decreases until high water is reached, and the rise ceases.

The falling tide behaves in a similar manner. The period at high or low water during which there is no apparent change of level is called **stand**. The difference in height between consecutive high and low waters is the **range**.

Figure 904 is a graphical representation of the rise and fall of the tide at New York during a 24-hour period. The curve has the general form of a variable sine curve.

905. Types of Tide

A body of water has a natural period of oscillation, dependent upon its dimensions. None of the oceans is a single oscillating body; rather each one is made up of several separate oscillating basins. As such basins are acted upon by the tide-producing forces, some respond more readily to daily or diurnal forces, others to semidiurnal forces, and others almost equally to both. Hence, tides are classified as one of three types, semidiurnal, diurnal, or mixed, according to the characteristics of the tidal pattern.

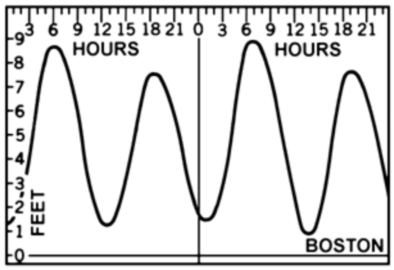

Figure 905a. Semidiurnal type of tide.

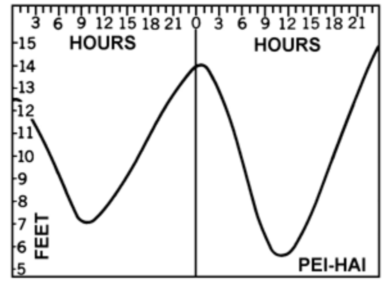

Figure 905b. Diurnal tide.

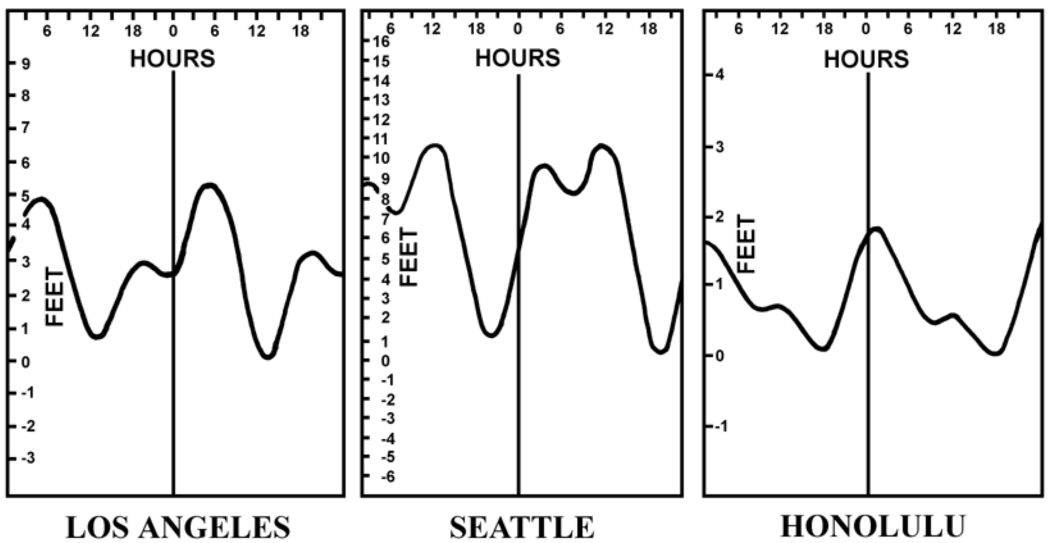

Figure 905c. Mixed tide.

In the **semidiurnal tide**, there are two high and two low waters each tidal day, with relatively small differences in the respective highs and lows. Tides on the Atlantic coast of the United States are of the semidiurnal type, which is illustrated in Figure 905a by the tide curve for Boston Harbor.

In the **diurnal tide**, only a single high and single low water occur each tidal day. Tides of the diurnal type occur along the northern shore of the Gulf of Mexico, in the Java Sea, the Gulf of Tonkin, and in a few other localities. The tide curve for Pei-Hai, China, illustrated in Figure 905b, is an example of the diurnal type.

In the **mixed tide**, the diurnal and semidiurnal oscillations are both important factors and the tide is characterized by a large inequality in the high water heights, low water heights, or in both. There are usually two high and two low waters each day, but occasionally the tide may become diurnal. Such tides are prevalent along the Pacific coast of the United States and in many other parts of the world. Examples of mixed types of tide are shown in Figure 905c. At Los Angeles, it is typical that the inequalities in the high and low waters are about the same. At Seattle the greater inequalities are typically in the low waters, while at Honolulu it is the high waters that have the greater inequalities.

906. Solar Tide

The natural period of oscillation of a body of water may accentuate either the solar or the lunar tidal oscillations. Though as a general rule the tides follow the Moon, the relative importance of the solar effect varies in different areas. There are a few places, primarily in the South Pacific and the Indonesian areas, where the solar oscillation is the more important, and at those places the high and low waters occur at about the same time each day. At Port Adelaide, Australia the solar and lunar semidiurnal oscillations are equal and nullify one another at neaps.

907. Special Tidal Effects

As a wave enters shallow water, its speed is decreased. Since the trough is shallower than the crest, it is retarded more, resulting in a steepening of the wave front. In a few estuaries, the advance of the low water trough is so much retarded that the crest of the rising tide overtakes the low, and advances upstream as a breaking wave called a **bore**. Bores that are large and dangerous at times of large tidal ranges may be mere ripples at those times of the month when the range is small. Examples occur in the Petitcodiac River in the Bay of Fundy, and at Haining, China, in the Tsientang Kaing. The tide tables indicate where bores occur.

Other special features are the **double low water** (as at Hoek Van Holland) and the **double high water** (as at Southampton, England). At such places there is often a slight fall or rise in the middle of the high or low water period. The practical effect is to create a longer period of stand at high or low tide. The tide tables list these and other peculiarities where they occur.

908. Variations in Range

Though the tide at a particular place can be classified as to type, it exhibits many variations during the month (Figure 908a). The range of the tide varies according to the intensity of the tide-producing forces, though there may be a lag of a day or two between a particular astronomic cause and the tidal effect.

The combined lunar-solar effect is obtained by adding the Moon's tractive forces vectorially to the Sun's tractive forces. The resultant tidal bulge will be predominantly lunar with modifying solar effects upon both the height of the tide and the direction of the tidal bulge. Special cases of interest occur during the times of new and full Moon (Figure 908b). With the Earth, Moon, and Sun lying approximately on the same line, the tractive forces of the Sun are acting in the same direction as the Moon's tractive forces (modified by declination effects). The resultant tides are called **spring tides**, whose ranges are greater than average.

Between the spring tides, the Moon is at first and third quarters. At those times, the tractive forces of the Sun are acting at approximately right angles to the Moon's tractive forces. The results are tides called **neap tides**, whose ranges are less than average.

With the Moon in positions between quadrature and new or full, the effect of the Sun is to cause the tidal bulge to either lag or precede the Moon (Figure 908c). These effects are called **priming** and **lagging** the tides.

Thus, when the Moon is at the point in its orbit nearest the Earth (at perigee), the lunar semidiurnal range is increased and **perigean tides** occur. When the Moon is farthest from the Earth (at apogee), the smaller **apogean tides** occur. When the Moon and Sun are in line and pulling together, as at new and full Moon, **spring tides** occur (the term spring has nothing to do with the season of year); when the Moon and Sun oppose each other, as at the quadratures, the smaller **neap tides** occur. When certain of these phenomena coincide, **perigean spring tides** and **apogean neap tides** occur.

These are variations in the semidiurnal portion of the tide. Variations in the diurnal portion occur as the Moon and Sun change declination. When the Moon is at its maximum semi-monthly declination (either north or south), **tropic tides** occur in which the diurnal effect is at a maximum. When it crosses the equator, the diurnal effect is a minimum and **equatorial tides** occur.

When the range of tide is increased, as at spring tides, there is more water available only at high tide; at low tide there is less, for the high waters rise higher and the low waters fall lower at these times. There is more water at neap low water than at spring low water. With tropic tides, there is usually more depth at one low water during the day than at the other. While it is desirable to know the meanings of these terms, the best way of determining the height of the tide at any place and time is to examine the tide predictions for the place as given in the tide tables, which take all these effects into account.

909. Tidal Cycles

Tidal oscillations go through a number of cycles. The shortest cycle, completed in about 12 hours and 25 minutes for a semidiurnal tide, extends from any phase of the tide to the next recurrence of the same phase. During a lunar day (averaging 24 hours and 50 minutes) there are two highs and two lows (two of the shorter cycles) for a semidiurnal tide. The Moon revolves around the Earth with respect to the Sun in a **synodical month** of about 29 1/2 days, commonly called the **lunar month**. The effect of the phase variation is completed in one-half of a synodical month or about 2 weeks as the Moon varies from new to full or full to new.

The effect of the Moon's declination is also repeated in one-half of a **tropical month** of 27 1/3 days, or about every 2 weeks. The cycle involving the Moon's distance requires an **anomalistic month** of about 27 1/2 days. The Sun's declination and distance cycles are respectively a half year and a year in length.

An important lunar cycle, called the **nodal period** or Metonic cycle (after Greek philosopher Meton, fifth century BC, who discovered the phenomenon) is 18.6 years (usually expressed in round figures as 19 years). For a tidal value, particularly a range, to be considered a true mean, it must be either based upon observations extended over this period of time, or adjusted to take account of variations known to occur during the nodal period.

The nodal period is the result of axis of the Moon's rotation being tilted 5 degrees with respect to the axis of the Earth's rotation. Since the Earth's axis is tilted 23.5 degrees with respect to the plane of its revolution around the sun, the combined effect is that the Moon's declination varies from 28.5 degrees to 18.5 degrees in a cycle lasting 18.6 years. For practical purposes, the nodal period can be con-

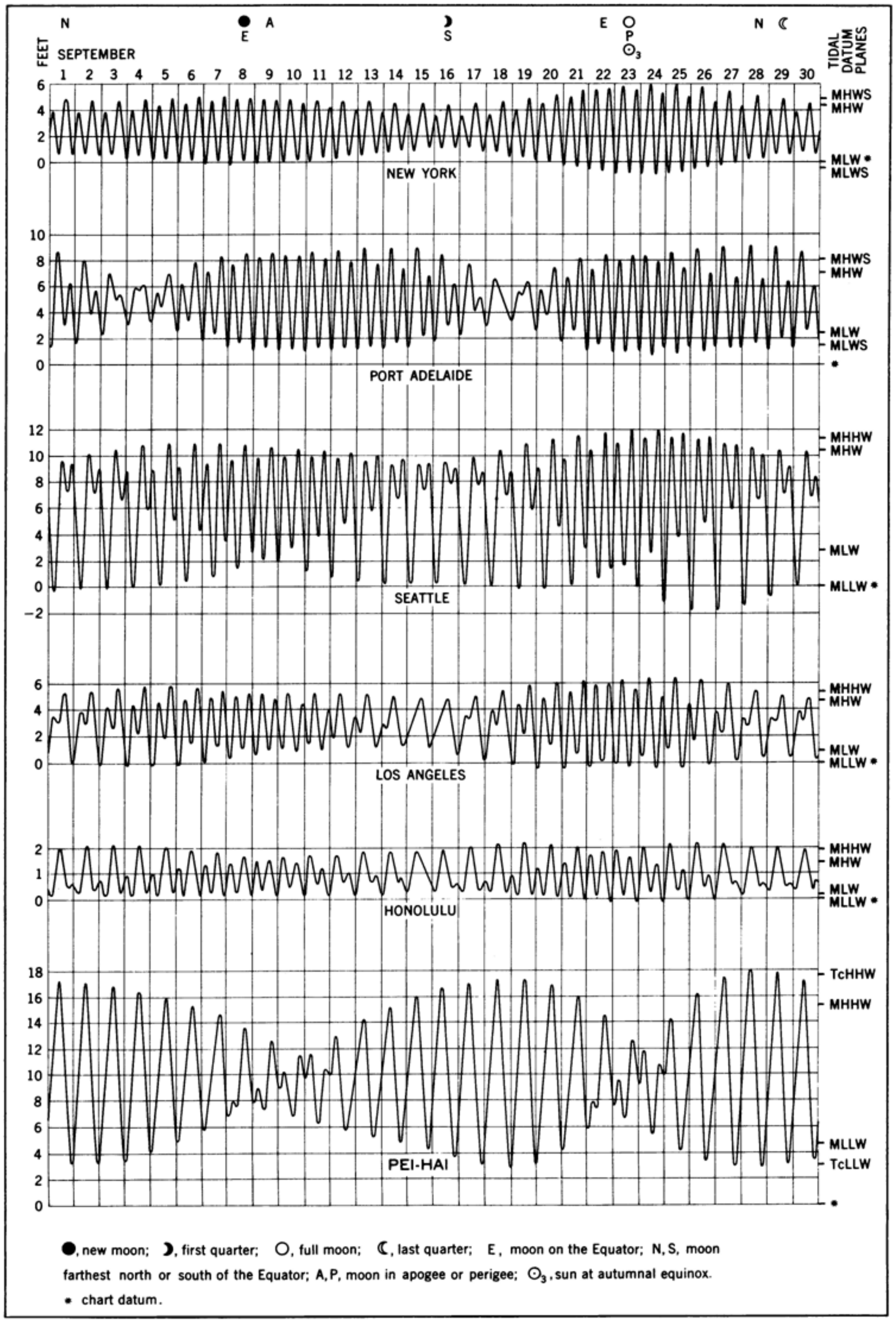

Figure 908a. Monthly tidal variations at various places.

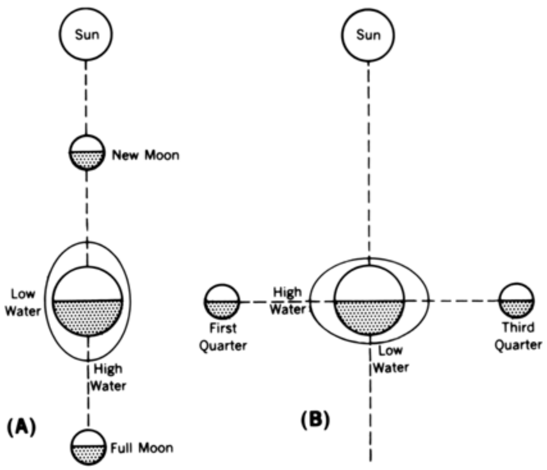

Figure 908b. (A) Spring tides occur at times of new and full Moon. Range of tide is greater than average since solar and lunar tractive forces act in same direction. (B) Neap ties occur at times of first and third quarters. Range of tide is less than average since solar and lunar tractive forces act at right angles.

sidered as the time between the Sun and Moon appearing in precisely the same relative positions in the sky.

910. Time of Tide

Since the lunar tide-producing force has the greatest effect in producing tides at most places, the tides "follow the Moon." Because the Earth rotates, high water lags behind both upper and lower meridian passage of the Moon. The **tidal day**, which is also the lunar day, is the time between consecutive transits of the Moon, or 24 hours and 50 minutes on the average. Where the tide is largely semidiurnal in type, the **lunitidal interval** (the interval between the Moon's meridian transit and a particular phase of tide) is fairly constant throughout the month, varying somewhat with the tidal cycles. There are many places, however, where solar or diurnal oscillations are effective in upsetting this relationship. The interval generally given is the average elapsed time from the meridian transit (upper or lower) of the Moon until the next high tide. This may be called **mean high water lunitidal interval** or **corrected** (or **mean**) **establishment**. The **common establishment** is the average interval on days of full or new Moon, and approximates the mean high water lunitidal interval.

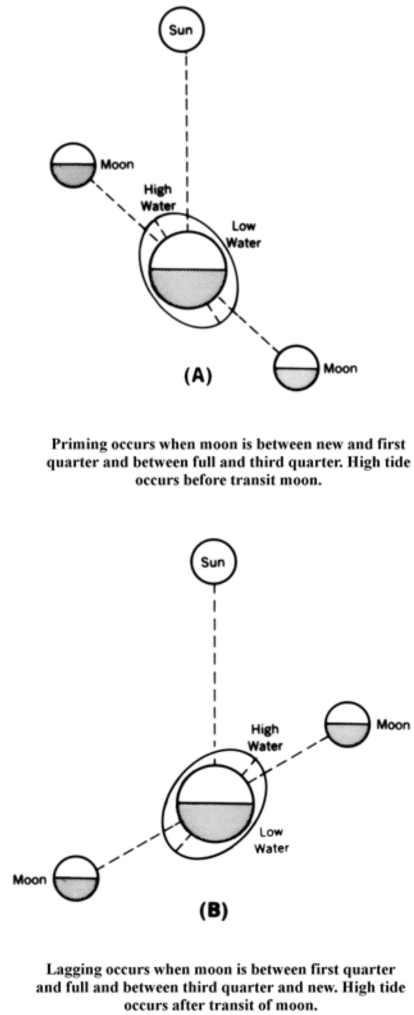

Figure 908c. Priming and lagging the tides.

In the ocean, the tide may be in the nature of a progressive wave with the crest moving forward, a stationary or standing wave which oscillates in a seesaw fashion, or a combination of the two. Consequently, caution should be used in inferring the time of tide at a place from tidal data for nearby places. In a river or estuary, the tide enters from the sea and is usually sent upstream as a progressive wave so that the tide occurs progressively later at various places upstream.

TIDAL DATUMS

911. Low Water Datums

A tidal datum is a given average tide level from which heights of tides and overhead clearances are measured. It is a vertical datum, but is not the same as vertical geodetic datum, which is a mathematical quantity developed as part of a geodetic system used for horizontal positioning. There are a number of tidal levels of reference that are important to the mariner. See Figure 911.

The most important level of reference is the **sounding datum** shown on charts. The sounding datum is sometimes referred to as the reference plane to distinguish it from vertical geodetic datum. Since the tide rises and falls continually while soundings are being taken during a hy-

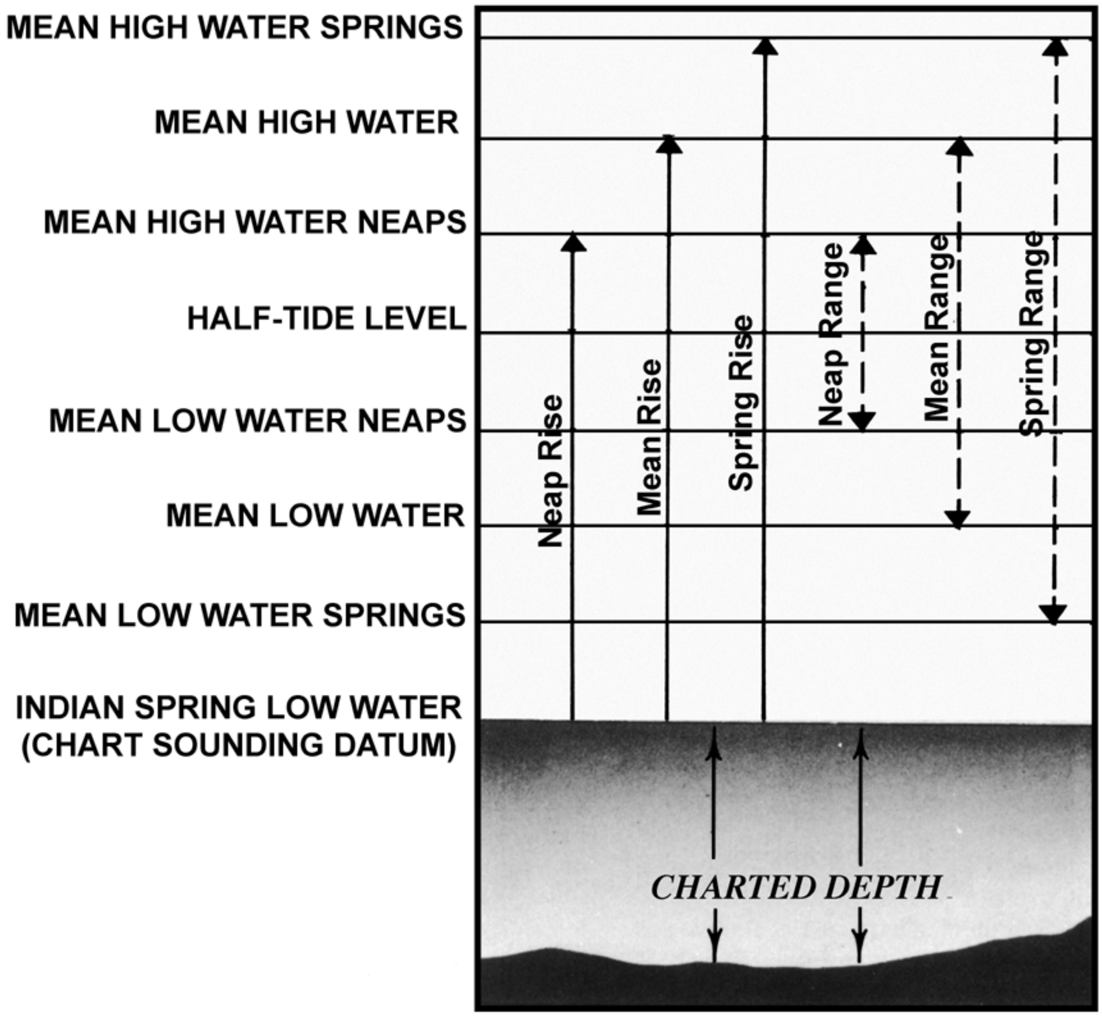

Figure 911. Variations in the ranges and heights of tide where the chart sounding datum is Indian Spring Low Water.

drographic survey, the tide is recorded during the survey so that soundings taken at all stages of the tide can be reduced to a common sounding datum. Soundings on charts show depths below a selected low water datum (occasionally mean sea level), and tide predictions in tide tables show heights above and below the same level. The depth of water available at any time is obtained by adding algebraically the height of the tide at the time in question to the charted depth.

By international agreement, the level used as chart datum should be low enough so that low waters do not fall very far below it. At most places, the level used is one determined from a mean of a number of low waters (usually over a 19 year period); therefore, some low waters can be expected to fall below it. The following are some of the datums in general use.

Mean low water (MLW) is the average height of all low waters at a given place. About half of the low waters fall below it, and half above.

Mean low water springs (MLWS), usually shortened to low water springs, is the average level of the low waters that occur at the times of spring tides.

Mean lower low water (MLLW) is the average height of the lower low waters of each tidal day.

Tropic lower low water (TcLLW) is the average height of the lower low waters (or of the single daily low waters if the tide becomes diurnal) that occur when the Moon is near maximum declination and the diurnal effect is most pronounced. This datum is not in common use as a tidal reference.

Indian spring low water (ISLW), sometimes called **Indian tide plane** or **harmonic tide plane**, is a low water datum that includes the spring effect of the semi-diurnal portion of the tide and the tropic effect of the diurnal portion. It is about the level of lower low water of mixed tides at the time that the Moon's maximum declination coincides with the time of new or full Moon.

Mean lower low water springs (MLLWS) is the average level of the lower of the two low waters on the days of spring tides.

Some lower datums used on charts are determined from tide observations and some are determined arbitrarily and later referred to the tide. Most of them fall close to one or the other of the following two datums.

Lowest normal low water is a datum that approximates the average height of monthly lowest low waters, discarding any tides disturbed by storms.

Lowest low water is an extremely low datum. It conforms generally to the lowest tide observed, or even somewhat lower. Once a tidal datum is established, it is sometimes retained for an indefinite period, even though it might differ slightly from a better determination from later observations. When this occurs, the established datum may be called **low water datum**, **lower low water datum**, etc. These datums are used in a limited area and primarily for river and harbor engineering purposes. Examples are Boston Harbor Low Water Datum and Columbia River Lower Low Water Datum.

Some sounding datums are based on the predicted tide rather than an average of observations. A British sounding datum that may be adopted internationally is the Lowest Astronomical Tide (LAT). LAT is the elevation of the lowest water level predicted in a 19-year period. Canadian coastal charts use a datum of Lower Low Water, Large Tide (LLWLT) which is the average of the lowest low waters, one from each of the 19 years of predictions.

Figure 911 illustrates variations in the ranges and heights of tides in a locality such as the Indian Ocean, where predicted and observed water levels are referenced to a chart sounding datum that will always cause them to be additive relative to the charted depth.

In areas where there is little or no tide, various other datums are used. For the Black Sea for instance, Mean Sea Level (MSL, sometimes referred to as Mean Water Level or MWL) is used, and is the average of the hourly heights observed over a period of time and adjusted to a 19-year period. In the United States, a Low Water Datum (LWD) is used in those coastal areas that have transitioned from tidal to non-tidal (e.g. Laguna Madre, Texas and Pamlico Sound, North Carolina) and is simply 0.5 foot below a computed MLW. For the Great Lakes, the United States and Canada use a separate LWD for each lake, which is designed to ensure that the actual water level is above the datum most of the time during the navigation season. Lake levels vary by several feet over a period of years.

Inconsistencies of terminology are found among charts of different countries and between charts issued at different times.

Large-scale charts usually specify the datum of soundings and may contain a tide note giving mean heights of the tide at one or more places on the chart. These heights are intended merely as a rough guide to the change in depth to be expected under the specified conditions. They should not be used for the prediction of heights on any particular day, which should be obtained from tide tables.

912. High Water Datums

Heights of terrestrial features are usually referred on nautical charts to a high water datum. This gives the mariner a margin of error when passing under bridges, overhead cables, and other obstructions. The one used on charts of the United States, its territories and possessions, and widely used elsewhere, is **mean high water (MHW)**, which is the average height of all high waters over a 19 year period. Any other high water datum in use on charts is likely to be higher than this. Other high water datums are **mean high water springs (MHWS)**, which is the average level of the high waters that occur at the time of spring tides; **mean higher high water (MHHW)**, which is the average height of the higher high waters of each tidal day; and **tropic higher high water (TcHHW)**, which is the average height of the higher high waters (or the single daily high waters if the tide becomes diurnal) that occur when the Moon is near maximum declination and the diurnal effect is most pronounced. A reference merely to "high water" leaves some doubt as to the specific level referred to, for the height of high water varies from day to day. Where the range is large, the variation during a 2 week period may be considerable.

Because there are periodic and apparent secular trends in sea level, a specific 19 year cycle (the **National Tidal Datum Epoch**) is issued for all United States datums. The National Tidal Datum Epoch officially adopted by the National Ocean Service is presently 1960 through 1978. The Epoch is reviewed for revision every 25 years.

TIDAL CURRENTS

913. Tidal and Nontidal Currents

Horizontal movement of water is called **current**. It may be either "tidal" and "nontidal." **Tidal current** is the periodic horizontal flow of water accompanying the rise and fall of the tide. **Nontidal current** includes all currents not due to the tidal movement. Nontidal currents include the permanent currents in the general circulatory system of the oceans as well as temporary currents arising from meteorological conditions. The current experienced at any time is usually a combination of tidal and nontidal currents.

914. General Features

Offshore, where the direction of flow is not restricted by any barriers, the tidal current is rotary; that is, it flows continuously, with the direction changing through all points of the compass during the tidal period. This rotation is caused by the Earth's rotation, and unless modified by local conditions, is clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. The speed usually varies throughout the tidal cycle, passing through two maximums in approximately opposite directions, and two minimums about halfway between the maximums in time and direction. Rotary currents can be depicted as in Figure 914a, by a series of arrows representing the direction and speed of the current at each hour. This is sometimes called a **current rose**. Because of the elliptical pattern formed by the ends of the arrows, it is also referred to as a **current ellipse**.

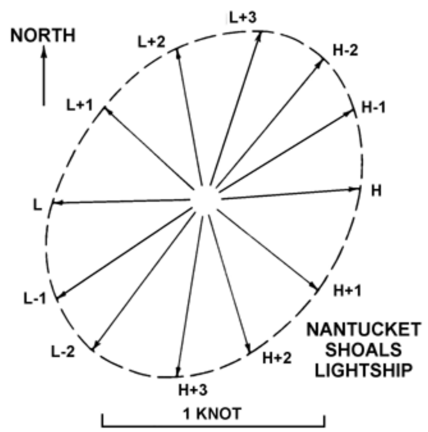

Figure 914a. Rotary tidal current. Times are hours before and after high and low tide at Nantucket Shoals. The bearing and length of each arrow represents the hourly direction and speed of the current.

In rivers or straits, or where the direction of flow is more or less restricted to certain channels, the tidal current is reversing; that is, it flows alternately in approximately opposite directions with an instant or short period of little or no current, called **slack water**, at each reversal of the current. During the flow in each direction, the speed varies from zero at the time of slack water to a maximum, called strength of flood or ebb, about midway between the slacks. Reversing currents can be indicated graphically, as in Figure 914b, by arrows that represent the speed of the current at each hour. The flood is usually depicted above the slack waterline and the ebb below it. The tidal current curve formed by the ends of the arrows has the same characteristic sine form as the tide curve. In illustrations and for certain other purposes it is convenient to omit the arrows and show only the curve.

A slight departure from the sine form is exhibited by the reversing current in a strait that connects two different tidal basins, such as the East River, New York. The tides at the two ends of a strait are seldom in phase or equal in range, and the current, called **hydraulic current**, is generated largely by the continuously changing difference in height of water at the two ends. The speed of a hydraulic current varies nearly as the square root of the difference in height. The speed reaches a maximum more quickly and remains at strength for a longer period than shown in Figure 914b, and the period of weak current near the time of slack is considerably shortened.

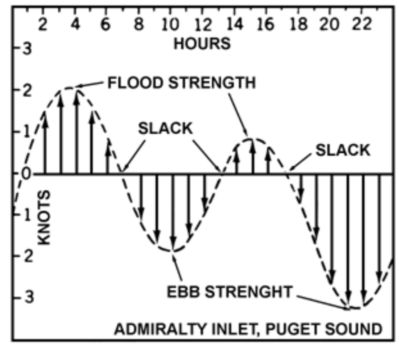

Figure 914b. Reversing tidal current.

The current direction, or **set**, is the direction toward which the current flows. The speed is sometimes called the **drift**. The term “velocity” is often used as the equivalent of “speed” when referring to current, although strictly speaking “velocity” implies direction as well as speed. The term “strength” is also used to refer to speed, but more often to greatest speed between consecutive slack waters. The movement toward shore or upstream is the **flood**, the movement away from shore or downstream is the **ebb**. In a purely semidiurnal current unaffected by nontidal flow, the flood and ebb each last about 6 hours and 13 minutes. But if there is either diurnal inequality or nontidal flow, the durations of flood and ebb may be quite unequal.

915. Types of Tidal Current

Tidal currents, like tides, may be of the **semidiurnal**, **diurnal**, or **mixed** type, corresponding to a considerable degree to the type of tide at the place, but often with a stronger semidiurnal tendency.

The tidal currents in tidal estuaries along the Atlantic coast of the United States are examples of the semidiurnal type of reversing current. Along the Gulf of Mexico coast, such as at Mobile Bay entrance, they are almost purely diurnal. At most places, however, the type is mixed to a greater or lesser degree. At Tampa and Galveston entrances there is only one flood and one ebb each day when the Moon is near its maximum declination, and two floods and two ebbs each day when the Moon is near the equator. Along the Pacific coast of the United States there are generally two floods and two ebbs every day, but one of the floods or ebbs has a greater speed and longer duration than the other, the inequality varying with the declination of the Moon.

The inequalities in the current often differ considerably from place to place even within limited areas, such as adjacent passages in Puget Sound and various passages between the Aleutian Islands. Figure 915a shows several types of re-

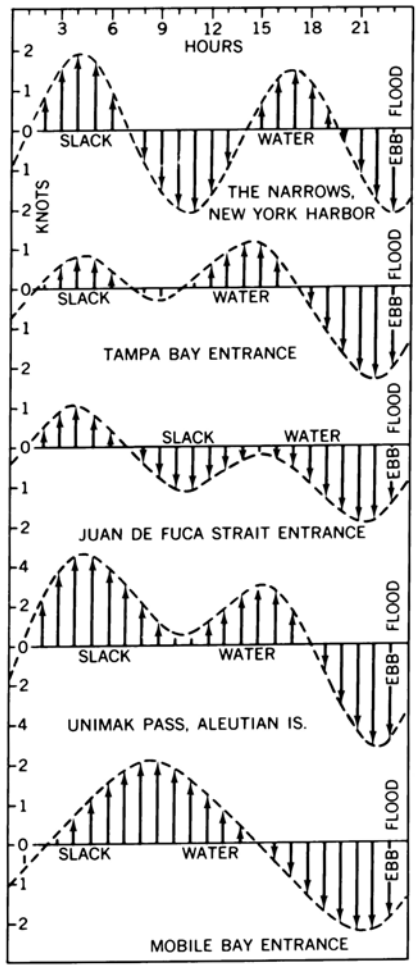

Figure 915a. Several types of reversing current. The pattern changes gradually from day to day, particularly for mixed types, passing through cycles.

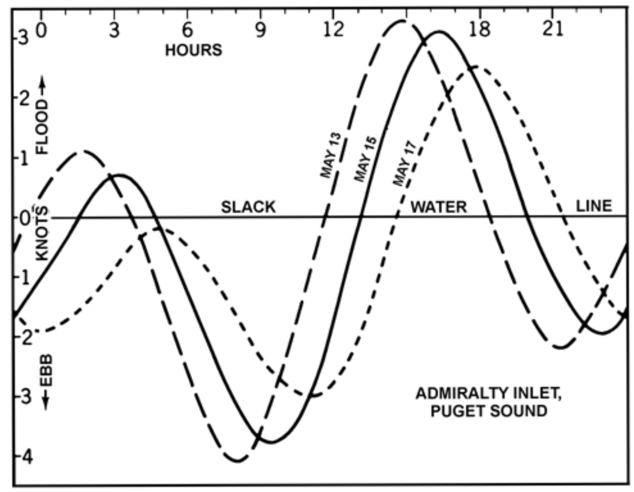

Figure 915b. Changes in a current of the mixed type. Note that each day as the inequality increases, the morning slacks draw together in time until on the 17th the morning flood disappears. On that day the current ebbs throughout the morning.

versing current. Figure 915b shows how the flood disappears as the diurnal inequality increases at one station.

Offshore rotary currents that are purely semidiurnal repeat the elliptical pattern each tidal cycle of 12 hours and 25 minutes. If there is considerable diurnal inequality, the plotted hourly current arrows describe a set of two ellipses of different sizes during a period of 24 hours and 50 minutes, as shown in Figure 915c, and the greater the diurnal inequality, the greater the difference between the sizes of the two ellipses. In a completely diurnal rotary current, the smaller ellipse disappears and only one ellipse is produced in 24 hours and 50 minutes.

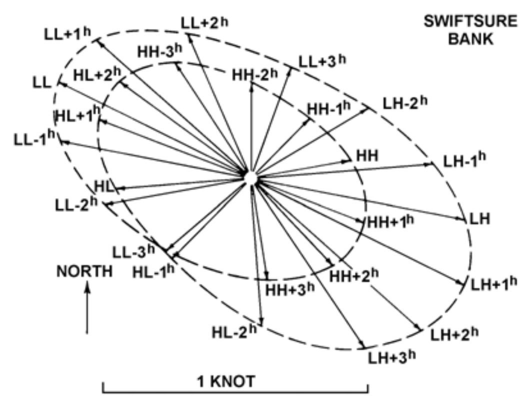

Figure 915c. Rotary tidal current with diurnal inequality. Times are in hours referred to tides (higher high, lower low, lower high, and higher low) at Swiftsure Bank.

916. Tidal Current Periods and Cycles

Tidal currents have periods and cycles similar to those of the tides, and are subject to similar variations, but flood and ebb of the current do not necessarily occur at the same times as the rise and fall of the tide.

The speed at strength increases and decreases during the 2 week period, month, and year along with the variations in the range of tide. Thus, the stronger spring and perigean currents occur near the times of new and full Moon and near the times of the Moon's perigee, or at times of spring and perigean tides; the weaker neap and apogean currents occur at the times of neap and apogean tides; and tropic currents with increased diurnal speeds or with larger diurnal inequalities in speed occur at times of tropic tides; and equatorial currents with a minimum diurnal effect occur at times of equatorial tides.

As with the tide, a mean value represents an average obtained from a 19 year series. Since a series of current observations is usually limited to a few days, and seldom covers more than a month or two, it is necessary to adjust the observed values, usually by comparison with tides at a nearby place, to obtain such a mean.

917. Effect of Nontidal Flow

The current existing at any time is seldom purely tidal, but usually includes also a nontidal current that is due to drainage, oceanic circulation, wind, or other causes. The method in which tidal and nontidal currents combine is best explained graphically, as in Figure 917a and Figure 917b. The pattern of the tidal current remains unchanged, but the curve is shifted from the point or line from which the currents are measured, in the direction of the nontidal current, and by an amount equal to it. It is sometimes more convenient graphically merely to move the line or point of origin in the opposite direction. Thus, the speed of the current flowing in the direction of the nontidal current is increased by an amount equal to the magnitude of the nontidal current, and the speed of the current flowing in the opposite direction is decreased by an equal amount.

In Figure 917a, a nontidal current is represented both in direction and speed by the vector AO. Since this is greater than the speed of the tidal current in the opposite direction, the point A is outside the ellipse. The direction and speed of the combined tidal and nontidal currents at any time is represented by a vector from A to that point on the curve representing the given time, and can be scaled from the graph. The strongest and weakest currents may no longer be in the directions of the maximum and minimum of the tidal current. If the nontidal current is northwest at 0.3 knot, it may be represented by BO, and all hourly directions and speeds will then be measured from B. If it is 1.0 knot, it will be represented by AO and the actual resultant hourly directions and speeds will be measured from A, as shown by the arrows.

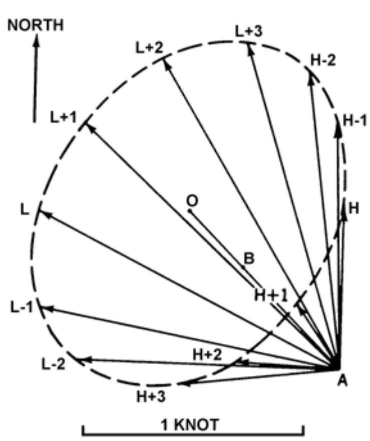

Figure 917a. Effect of nontidal current on the rotary tidal current of Figure 914a.

In a reversing current (Figure 917b), the effect is to advance the time of one slack, and to retard the following one. If the speed of the nontidal current exceeds that of the reversing tidal current, the resultant current flows continuously in one direction without coming to a slack. In this case, the speed varies from a maximum to a minimum and back to a maximum in each tidal cycle. In Figure 917b, the horizontal line A represents slack water if only tidal currents are present. Line B represents the effect of a 0.5 knot nontidal ebb, and line C the effect of a 1.0 knot nontidal ebb. With the condition shown at C there is only one flood each tidal day. If the nontidal ebb were to increase to approximately 2 knots, there would be no flood, two maximum ebbs and two minimum ebbs occurring during a tidal day.

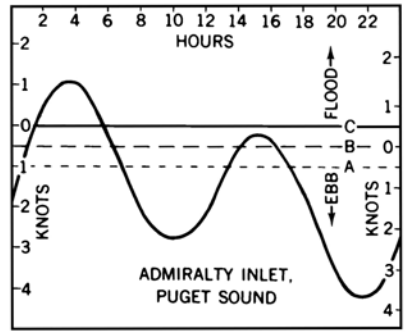

Figure 917b. Effect of nontidal current on the reversing tidal current of Figure 914b.

918. Time of Tidal Current and Time of Tide

At many places where current and tide are both semidiurnal, there is a definite relationship between times of current and times of high and low water in the locality. Current atlases and notes on nautical charts often make use of this relationship by presenting for particular locations, the direction and speed of the current at each succeeding hour after high and low water, at a place for which tide predictions are available.

Where there is considerable diurnal inequality in tide or current, or where the type of current differs from the type of tide, the relationship is not constant, and it may be hazardous to try to predict the times of current from times of tide. Note the current curve for Unimak Pass in the Aleutians in Figure 915a. It shows the current as predicted in the tidal current tables. Predictions of high and low waters in the tide tables might have led one to expect the current to change from flood to ebb in the late morning, whereas actually the current continued to run flood with some strength at that time.

Since the relationship between times of tidal current and tide is not the same everywhere, and may be variable at the same place, one should exercise extreme caution in using general rules. The belief that slacks occur at local high and low tides and that the maximum flood and ebb occur when the tide is rising or falling most rapidly may be approximately true at the seaward entrance to, and in the upper reaches of, an inland tidal waterway. But generally this is not true in other parts of inland waterways. When an inland waterway is extensive or its entrance constricted, the slacks in some parts of the waterway often occur midway between the times of high and low tide. Usually in such waterways the relationship changes from place to place as one progresses upstream, slack water getting progressively closer in time to the local tide maximum until at the head of tidewater (the inland limit of water affected by a tide) the slacks occur at about the times of high and low tide.

919. Relationship Between Speed of Current and Range of Tide

The speed of the tidal current is not necessarily consistent with the range of tide. It may be the reverse. For example, currents are weak in the Gulf of Maine where the tides are large, and strong near Nantucket Island and in Nantucket Sound where the tides are small. However, at any one place the speed of the current at strength of flood and ebb varies during the month in about the same proportion as the range of tide, and this relationship can be used to determine the relative strength of currents on any given day.

920. Variation Across an Estuary

In inland tidal estuaries the time of tidal current varies across the channel from shore to shore. On the average, the current turns earlier near shore than in midstream, where the speed is greater. Differences of half an hour to an hour are not uncommon, but the difference varies and the relationship may be nullified by the effect of nontidal flow.

The speed of the current also varies across the channel, usually being greater in midstream or midchannel than near shore, but in a winding river or channel the strongest currents occur near the concave shore, or the outside corner of the curve. Near the opposite (convex) shore the currents are weak or eddying.

921. Variation with Depth

In tidal rivers the subsurface current acting on the lower portion of a ship’s hull may differ considerably from the surface current. An appreciable subsurface current may be present when the surface movement appears to be practically slack, and the subsurface current may even be flowing with appreciable speed in the opposite direction to the surface current.

In a tidal estuary, particularly in the lower reaches where there is considerable difference in density from top to bottom, the flood usually begins earlier near the bottom than at the surface. The difference may be an hour or two, or as little as a few minutes, depending upon the estuary, the location in the estuary, and freshet conditions. Even when the freshwater runoff becomes so great as to prevent the surface current from flooding, it may still flood below the surface. The difference in time of ebb from surface to bottom is normally small but subject to variation with time and location.

The ebb speed at strength usually decreases gradually from top to bottom, but the speed of flood at strength often is stronger at subsurface depths than at the surface.

922. Tidal Current Observations

Observations of current are made with sophisticated electronic **current meters**. Current meters are suspended from a buoy or anchored to the bottom with no surface marker at all. Very sensitive current meters measure and record deep ocean currents; these are later recovered by triggering a release mechanism with a signal from the surface. Untended current meters either record data internally or send it by radio to a base station on ship or land. The period of observation varies from a few hours to as long as 6 months.

TIDE AND CURRENT PREDICTION

923. Tidal Height Predictions

To measure the height of tides, hydrographers select a reference level, sometimes referred to as the reference plane, or vertical datum. This vertical tidal datum is not the same as the vertical geodetic datum. Soundings shown on the largest scale charts are the vertical distances from this datum to the bottom. At any given time the actual depth is this charted depth plus the height of tide. In most places the reference level is some form of low water. But all low waters at a given place are not the same height, and the selected reference level is seldom the lowest tide occurring at the place. When lower tides occur, these are indicated in the tide tables by a negative sign. Thus, at a spot where the charted depth is 15 feet, the actual depth is 15 feet plus the tidal height. When the tide is three feet, the depth is 15 + 3 = 18 feet. When it is -1 foot, the depth is 15 - 1 = 14 feet. The actual depth can be less than the charted depth. In an area where there is a considerable range of tide (the difference between high water and low water), the height of tide might be an important consideration when using soundings to determine if the vessel is in safe water.

The heights given in the tide tables are predictions, and when assumed conditions vary considerably, the predictions shown may be considerably in error. Heights lower than predicted can be anticipated when the atmospheric pressure is higher than normal, or when there is a persistent strong offshore wind. The greater the range of tide, the less reliable are the predictions for both height and current.

924. Tidal Heights

The nature of the tide at any place can best be determined by observation. The predictions in tide tables and the tidal data on nautical charts are based upon detailed observations at specific locations, instead of theoretical predictions.

Tidal elevations are usually observed with a continuously recording gage. A year of observations is the minimum length desirable for determining the harmonic constants used in prediction. For establishing mean sea level and long-term changes in the relative elevations of land and sea, as well as for other special uses, observations have been made over periods of 20, 30, and even 120 years at important locations. Observations for a month or less will establish the type of tide and suffice for comparison with a longer series of observations to determine tidal differences and constants.

Mathematically, the variations in the lunar and solar tide-producing forces, such as those due to changing phase, distance, and declination, are considered as separate constituent forces, and the harmonic analysis of observations reveals the response of each constituent of the tide to its corresponding force. At any one place this response remains constant and is shown for each constituent by **harmonic constants** which are in the form of a phase angle for the time relation and an amplitude for the height. Harmonic constants are used in making technical studies of the tide and in tidal predictions on computers. The tidal predictions in most published tide tables are produced by computer.

925. Meteorological Effects

The foregoing discussion of tidal behavior assumes normal weather conditions. However, sea level is also affected by wind and atmospheric pressure. In general, onshore winds raise the level and offshore winds lower it, but the amount of change varies at different places. During periods of low atmospheric pressure, the water level tends to be higher than normal. For a stationary low, the increase in elevation can be found by the formula

$$R_0=0.01(1010 - P),$$

in which R_0 is the increase in elevation in meters and P is the atmospheric pressure in hectopascals. This is equal approximately to 1 centimeter per hectopascal depression, or about 13.6 inches per inch depression. For a moving low, the increase in elevation is given by the formula

$$R= \frac{R_0}{1-\frac{C^2}{gh}}$$

in which R is the increase in elevation in feet, R_0 is the increase in meters for a stationary low, C is the rate of motion of the low in feet per second, g is the acceleration due to gravity (32.2 feet per second per second), and h is the depth of water in feet.

Where the range of tide is very small, the meteorological effect may sometimes be greater than the normal tide. Where a body of water is large in area but shallow, high winds can push the water from the windward to the lee shore, creating much greater local differences in water levels than occurs normally, and partially or completely masking the tides. The effect is dependent on the configuration and depth of the body of water relative to the wind direction, strength and duration.

926 Tidal Current Predictions

Tidal currents are due primarily to tidal action, but other causes are often present. The ***Tidal Current Tables*** give the best prediction of total current. Following heavy rains or a drought, a river's current prediction may be considerably in error. Set and drift may vary considerably over different parts of a harbor, because differences in bathymetry from place to place affect current. Since this is usually an area where small errors in a vessel's position are crucial, a knowledge of predicted currents, particularly in reduced visibility, is important. Strong currents occur mostly in narrow passages connecting larger bodies of water. Currents of more than 5 knots are sometimes encountered at the Golden Gate in San Francisco, and currents of more than 13 knots sometimes occur at Seymour Narrows, British Columbia.

In straight portions of rivers and channels, the strongest currents usually occur in the middle of the channel. In curved portions the swiftest currents (and deepest water) usually occur near the outer edge of the curve. Countercurrents and eddies may occur on either side of the main current of a river or narrow passage, especially near obstructions and in bights.

In general, the range of tide and the velocity of tidal current are at a minimum in the open ocean or along straight coasts. The greatest tidal effects are usually encountered in estuaries, bays, and other coastal indentations. A vessel proceeding along an indented coast may encounter a set toward or away from the shore; a similar set is seldom experienced along a straight coast.

PUBLICATIONS FOR PREDICTING TIDES AND CURRENTS

927. *Tide Tables*

Usually, tidal information is obtained from tide and tidal current tables, or from specialized computer software or calculators. However, if these are not available, or if they do not include information at a desired place, the mariner may be able to obtain locally the **mean high water lunitidal interval** or the **high water full and change**. The approximate time of high water can be found by adding either interval to the time of transit (either upper or lower) of the Moon. Low water occurs approximately 1/4 tidal day (about $6^h\ 12^m$) before and after the time of high water. The actual interval varies somewhat from day to day, but approximate results can be obtained in this manner. Similar information for tidal currents (**lunicurrent interval**) is seldom available.

The National Ocean Service (NOS) has traditionally published hard copy tide tables and tidal current tables. Tide and tidal current data continue to be updated by NOS, but hardcopy publication has been transferred to private companies working with NOS data, published on CD-ROM.

Tidal data for various parts of the world is published in 4 volumes by the National Ocean Service. These volumes are:

- Central and Western Pacific Ocean and Indian Ocean
- East Coast of North and South America (including Greenland)
- Europe and West Coast of Africa
- West Coast of North and South America (including the Hawaiian Islands)

A small separate volume, the Alaskan Supplement, is also published.

Each volume has 5 common tables:

- **Table 1** contains a complete list of the predicted times and heights of the tide for each day of the year at a number of places designated as **reference stations**.
- **Table 2** gives tidal differences and ratios which can be used to modify the tidal information for the reference stations to make it applicable to a relatively large number of **subordinate stations**.
- **Table 3** provides information for finding the approximate height of the tide at any time between high water and low water.
- **Table 4** is a sunrise-sunset table at five-day intervals for various latitudes from 76°N to 60°S (40°S in one volume).
- **Table 5** provides an adjustment to convert the local mean time of Table 4 to zone or standard time.

For the East Coast and West Coast volumes, each contains a Table 6, a moonrise and moonset table; Table 7 for conversion from feet to centimeters; Table 8, a table of estimated tide prediction accuracies; a glossary of terms; and an index to stations. Each table is preceded by a complete explanation. Sample problems are given where necessary. The inside back cover of each volume contains a calendar of critical astronomical data to help explain the variations of the tide during each month and throughout the year.

928. Tide Predictions for Reference Stations

For each day, the date and day of week are given, and the time and height of each high and low water are listed in chronological order. Although high and low waters are not labeled as such, they can be distinguished by the relative heights given immediately to the right of the times. If two high tides and two low tides occur each tidal day, the tide is semidiurnal. Since the tidal day is longer than the civil day (because of the revolution of the Moon eastward around the Earth), any given tide occurs later each day. Because of later times of corresponding tides from day to day, certain days have only one high water or only one low water.

929. Tide Predictions for Subordinate Stations

For each subordinate station listed, the following information is given:

1. **Number**. The stations are listed in geographical order and assigned consecutive numbers. Each volume contains an alphabetical station listing correlating the station with its consecutive number to assist in finding the entry in Table 2.
2. **Place**. The list of places includes both subordinate and reference stations; the latter are in bold type.
3. **Position**. The approximate latitude and longitude are given to assist in locating the station. The latitude is north or south, and the longitude east or west, depending upon the letters (N, S, E, W) next above the entry. These may not be the same as those at the top of the column.
4. **Differences**. The differences are to be applied to the predictions for the reference station, shown in capital letters above the entry. Time and height differences are given separately for high and low waters. Where differences are omitted, they are either unreliable or unknown.
5. **Ranges**. Various ranges are given, as indicated in the tables. In each case this is the difference in height between high water and low water for the tides indicated.
6. **Mean tide level**. This is the average between mean low and mean high water, measured from chart datum.

The **time difference** is the number of hours and minutes to be applied to the reference station time to find the time of the corresponding tide at the subordinate station. This interval is added if preceded by a plus sign (+) and subtracted if preceded by a minus sign (-). The results obtained by the application of the time differences will be in the zone time of the time meridian shown directly above the difference for the subordinate station. Special conditions occurring at a few stations are indicated by footnotes on the applicable pages. In some instances, the corresponding tide falls on a different date at reference and subordinate stations.

Height differences are shown in a variety of ways. For most entries, separate height differences in feet are given for high water and low water. These are applied to the height given for the reference station. In many cases a ratio is given for either high water or low water, or both. The height at the reference station is multiplied by this ratio to find the height at the subordinate station. For a few stations, both a ratio and difference are given. In this case the height at the reference station is first multiplied by the ratio, and the difference is then applied. An example is given in each volume of tide tables. Special conditions are indicated in the table or by footnote. For example, a footnote indicates that "Values for the Hudson River above George Washington Bridge are based upon averages for the six months May to October, when the fresh-water discharge is a minimum."

930. Finding Height of Tide at any Time

Table 3 provides means for determining the approximate height of tide at any time. It assumes that plotting height versus time yields a sine curve. Actual values may vary from this. The explanation of the table contains directions for both mathematical and graphical solutions. Though the mathematical solution is quicker, if the vessel's ETA changes significantly, it will have to be done for the new ETA. Therefore, if there is doubt about the ETA, the graphical solution will provide a plot of predictions for several hours and allow quick reference to the predicted height for any given time. This method will also quickly show at what time a given depth of water will occur. Figure 930a shows the OPNAV form used to calculate heights of tides. Figure 930b shows the importance of calculating tides in shallow water.

OPNAV 3530/40 (4-73)
HT OF TIDE

Date		
Location		
Time		
Ref Sta		
HW Time Diff		
LW Time Diff		
HW Ht Diff		
LW Ht Diff		
Ref Sta HW/LW Time		
HW/LW Time Diff		
Sub Sta HW/LW Time		
Ref Sta HW/LW Ht		
HW/LW Ht Diff		
Sub Sta HW/LW Ht		
Duration	**Rise**	
	Fall	
Time Fm	**Near**	
	Tide	
Range of Tide		
Ht of Neat Tide		
Corr Table 3		
Ht of Tide		
Charted Depth		
Depth of Water		
Draft		
Clearance		

Figure 930a. OPNAV 3530/40 Tide Form.

931. *Tidal Current Tables*

Tidal Current Tables are somewhat similar to *Tide Tables*, but the coverage is less extensive. NOS publishes 2 volumes on an annual basis: Atlantic Coast of North America, and Pacific Coast of North America and Asia. Each of the two volumes is arranged as follows:

Each volume also contains current diagrams and instructions for their use. Explanations and examples are given in each table.

- **Table 1** contains a complete list of predicted times of maximum currents and slack water, with the velocity of the maximum currents, for a number of reference stations.
- **Table 2** gives differences, ratios, and other information related to a relatively large number of subordinate

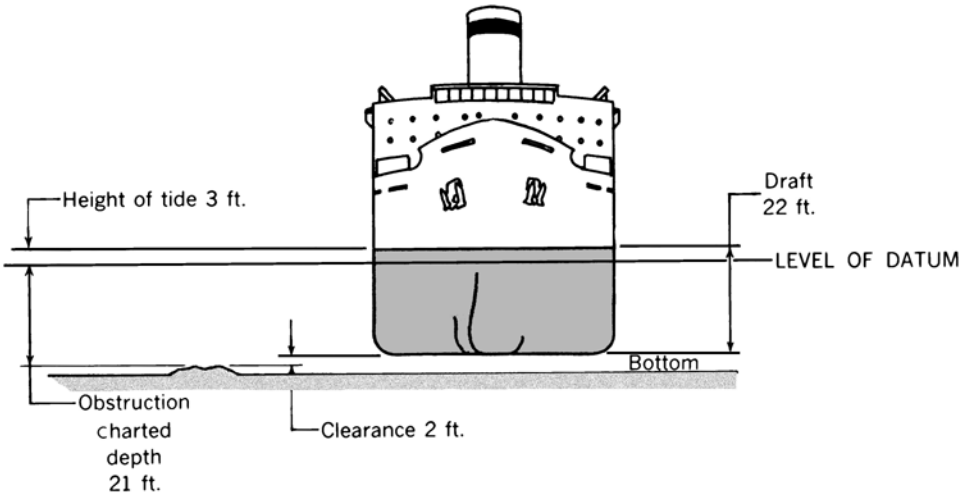

Figure 930b. Height of tide required to pass clear of charted obstruction.

stations.

- **Table 3** provides information to determine the current's velocity at any time between entries in tables 1 and 2.
- **Table 4** gives duration of slack, or the number of minutes the current does not exceed stated amounts, for various maximum velocities.
- **Table 5** (Atlantic Coast of North America only) gives information on rotary tidal currents.

The volumes also contain general descriptive information on wind-driven currents, combination currents, and information such as Gulf Stream currents for the east coast and coastal currents on the west coast.

932. Tidal Current Prediction for Reference Stations

For each day, the date and day of week are given; current information follows. If the cycle is repeated twice each tidal day, currents are semidiurnal. On most days there are four slack waters and four maximum currents, two floods (F) and two ebbs (E). However, since the tidal day is longer than the civil day, the corresponding condition occurs later each day, and on certain days there are only three slack waters or three maximum currents. At some places, the current on some days runs maximum flood twice, but ebbs only once, a minimum flood occurring in place of the second ebb. The tables show this information.

933. Tidal Current Predictions for Subordinate Stations

For each subordinate station listed in Table 2 of the tidal current tables, the following information is given:

1. **Number**: The stations are listed in geographical order and assigned consecutive numbers, as in the tide tables. Each volume contains an alphabetical station listing correlating the station with its consecutive number to assist in locating the entry in Table 2.
2. **Place**: The list of places includes both subordinate and reference stations, the latter given in bold type.
3. **Position**: The approximate latitude and longitude are given to assist in locating the station. The latitude is north or south and the longitude east or west as indicated by the letters (N, S, E, W) next above the entry. The current given is for the center of the channel unless another location is indicated by the station name.
4. **Time difference**: Two time differences are tabulated. One is the number of hours and minutes to be applied to the tabulated times of slack water at the reference station to find the times of slack waters at the subordinate station. The other time difference is applied to the times of maximum current at the reference station to find the times of the corresponding maximum current at the subordinate station. The intervals, which are added or subtracted in accordance with their signs, include any difference in time between the two stations, so that the answer is correct for the standard time of the subordinate station. Limited application and special conditions are indicated by footnotes.
5. **Velocity ratios**: Speed of the current at the subordinate station is the product of the velocity at the reference station and the tabulated ratio. Separate ratios may be given for flood and ebb currents. Special conditions are indicated by footnotes.
6. **Average Speeds and Directions**: Minimum and maximum velocities before flood and ebb are listed for each station, along with the true directions of the flow. Minimum velocity is not always 0.0 knots.

934. Finding Velocity of Tidal Current at any Time

Table 3 of the tidal current tables provides means for determining the approximate velocity at any time. Directions are given in an explanation preceding the table. Figure 934 shows the OPNAV form used for current prediction.

935. Duration of Slack Water

The predicted times of slack water listed in the tidal current tables indicate the instant of zero velocity. There is a period each side of slack water, however, during which the current is so weak that for practical purposes it may be considered negligible. Table 4 of the tidal current tables gives, for various maximum currents, the approximate period of time during which currents not exceeding 0.1 to 0.5 knots will be encountered. This period includes the last of the flood or ebb and the beginning of the following flood or ebb; that is, half of the duration will be before and half after the time of slack water.

When there is a difference between the velocities of the maximum flood and ebb preceding and following the slack for which the duration is desired, it will be sufficiently accurate to find a separate duration for each maximum velocity and average the two to determine the duration of the weak current.

Of the two sub-tables of Table 4, Table A is used for all places except those listed for Table B; Table B is used for just the places listed and the stations in Table 2 which are referred to them.

936. Additional Tide Prediction Publications

NOS also publishes a special *Regional Tide and Tidal Current Table for New York Harbor to Chesapeake Bay*, and a *Tidal Circulation and Water Level Forecast Atlas for Delaware River and Bay*.

937. *Tidal Current Charts*

Tidal Current charts present a comprehensive view of the hourly velocity of current in different bodies of water. They also provide a means for determining the current's velocity at various locations in these waters. The arrows show the direction of the current; the figures give the speed in knots at the time of spring tides. A weak current is defined as less than 0.1 knot. These charts depict the flow of the tidal current under normal weather conditions. Strong winds and freshets, however, may cause nontidal currents, considerably modifying the velocity indicated on the charts.

Tidal Current charts are provided (1994) for Boston Harbor, Charleston Harbor SC, Long Island Sound and Block Island Sound, Narragansett Bay, Narragansett Bay to Nantucket Sound, Puget Sound (Northern Part), Puget Sound (Southern Part), Upper Chesapeake Bay, and Tampa Bay.

OPNAV 3530/40 (4-73)
VEL OF CURRENT

Date	
Location	
Time	
Ref Sta	
Time Diff Stack Water	
Time Diff Max Current	
Vel Ratio Max Flood	
Vel Ratio Max Ebb	
Flood Dir	
Ebb Dir	
Ref Sta Stack Water Time	
Time Diff	
Local Sta Stack Water Time	
Ref Sta Max Current Time	
Time Diff	
Local Sta Max Current Time	
Ref Sta Max Current Vel	
Vel Ratio	
Local Sta Max Current Vel	
Int Between Slack and Desired Time	
Int Between Slack and Max Current	
Max Current	
Factor Table 3	
Velocity	
Direction	

Figure 934. OPNAV 3530/41 Current Form.

The tidal current's velocity varies from day to day as a function of the phase, distance, and declination of the Moon. Therefore, to obtain the velocity for any particular day and hour, the spring velocities shown on the charts must be modified by correction factors. A correction table given in the charts can be used for this purpose.

All of the charts except Narragansett Bay require the use of the annual *Tidal Current Tables*. Narragansett Bay requires use of the annual *Tide Tables*.

938. Current Diagrams

A current diagram is a graph showing the velocity of the current along a channel at different stages of the tidal current cycle. The current tables include diagrams for Martha's Vineyard and Nantucket Sounds (one diagram); East River, New York; New York Harbor; Delaware Bay and River (one diagram); and Chesapeake Bay. These diagrams are no longer published by NOS, but are available privately and remain useful as they are not ephemeral.

On Figure 938, each vertical line represents a given instant identified by the number of hours before or after slack water at The Narrows. Each horizontal line represents a distance from Ambrose Channel entrance, measured along the usually traveled route. The names along the left margin are placed at the correct distances from Ambrose Channel entrance. The current is for the center of the channel opposite these points. The intersection of any vertical line with any horizontal line represents a given moment in the current cycle at a given place in the channel. If this intersection is in a shaded area, the current is flooding; if in an unshaded area, it is ebbing. The velocity can be found by interpolation between the numbers given in the diagram. The given values are averages. To find the value at any time, multiply the velocity found from the diagram by the ratio of maximum velocity of the current involved to the maximum shown on the diagram. If the diurnal inequality is large, the accuracy can be improved by altering the width of the shaded area to fit conditions. The diagram covers 1 1/2 current cycles, so that the right 1/3 duplicates the left 1/3.

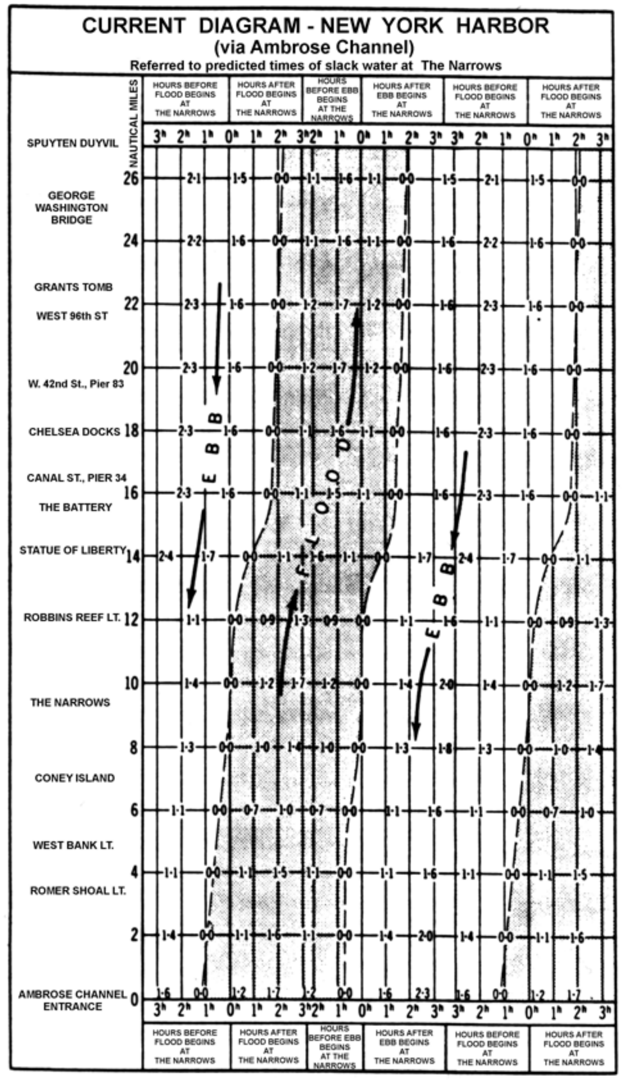

Figure 938. Current diagram for New York Harbor.

Use Table 1 or 2 to determine the current for a single station. The current diagrams are intended for use in either of two ways: to determine a favorable time for passage through the channel and to find the average current to be expected during a passage through the channel. For both of these uses, a number of "velocity lines" are provided. When the appropriate line is transferred to the correct part of the diagram, the current to be encountered during passage is indicated along the line.

If the transferred velocity line is partly in a flood current area, all ebb currents (those increasing the ship's velocity) are given a positive sign (+), and all flood currents a negative sign (-). A separate ratio should be determined for each current (flood or ebb), and applied to the entries for that current. In the Chesapeake Bay, it is common for an outbound vessel to encounter three or even four separate currents during passage. Under the latter condition, it is good practice to multiply each current taken from the diagram by the ratio for the current involved.

If the time of starting the passage is fixed, and the current during passage is desired, the starting time is identified in terms of the reference tidal cycle. The velocity line is then drawn through the intersection of this vertical time line and the horizontal line through the place. The average current is then determined in the same manner as when the velocity line is located as described above.

939. Computer Predictions

Until recently, tidal predictions were compiled only on mainframe or minicomputers and then put into hardcopy table form for the mariner. There are several types of commercial software available now for personal computers (PC's) that provide digital versions of the NOS tide tables and also graph the tidal heights. The tabular information and graphs can be printed for the desired locations for pre-voyage planning. There are also several types of specialized hand-held calculators and tide clocks that can be used to predict tides for local areas.

Newer versions of PC software use the actual harmonic constants available for locations, the prediction equation, and digital versions of Table 2 in the *Tide Tables* to produce even more products for the navigator's use. Since NOS has published the data, even inexpensive navigation electronics such as handheld GPS receivers and plotters for small craft navigation often include graphic tide tables.

Emerging applications include integration of tidal prediction with positioning systems and vessel traffic systems which are now moving towards full use of GPS. In addition, some electronic chart systems are already able to integrate tide prediction information. Many of these new systems will also use real-time water level and current information. Active research also includes providing predictions of total water level that will include not only the tidal prediction component, but also the weather-related component.