CHAPTER 5
WATER LEVELS AND FLOW

1. INTRODUCTION

The purpose of this chapter is to provide the hydrographer and technical reader the fundamental information required to understand and apply water levels, derived water level products and datums, and water currents to carry out field operations in support of hydrographic surveying and mapping activities. The hydrographer is concerned not only with the elevation of the sea surface, which is affected significantly by tides, but also with the elevation of lake and river surfaces, where tidal phenomena may have little effect. The term ‘tide’ is traditionally accepted and widely used by hydrographers in connection with the instrumentation used to measure the elevation of the water surface, though the term ‘water level’ would be more technically correct. The term ‘current’ similarly is accepted in many areas in connection with tidal currents; however water currents are greatly affected by much more than the tide producing forces. The term ‘flow’ is often used instead of currents.

Tidal forces play such a significant role in completing most hydrographic surveys that tide producing forces and fundamental tidal variations are only described in general with appropriate technical references in this chapter. It is important for the hydrographer to understand why tide, water level and water current characteristics vary both over time and spatially so that they are taken fully into account for survey planning and operations which will lead to successful production of accurate surveys and charts.

Because procedures and approaches to measuring and applying water levels, tides and currents vary depending upon the country, this chapter covers general principles using documented examples as appropriate for illustration.

2. TIDES AND WATER LEVELS

2.1 Principles of Tides and Water Levels

The observed tides at any given port are the result of many factors, including the response of the ocean basin to the tide producing forces, to the modifications of the tide due to shallow water effects of local embayments and rivers, to the regional and local effects of weather on water levels.

2.1.1 Astronomical Tide Producing Forces

At the surface of the Earth, the Earth’s gravitational attraction acts in a direction inward toward its centre of mass and thus holds the ocean waters confined to this surface. However, the gravitational forces of the Moon and Sun, and centrifugal force of the Sun-Earth-Moon system, act externally upon the Earth's ocean waters. These external forces are exerted as tide-producing, or tractive forces. Their affects are superimposed upon the Earth’s gravitational force and act to draw the ocean waters horizontally to various points on the Earth’s surface.

A high tide is produced in ocean waters by the ‘heaping’ action resulting from the horizontal flow of water toward the region of maximum attraction of the combined lunar and solar gravitational forces. An additional high tide is produced at a position on the opposite side of the Earth, where the centrifugal force of the orbiting system overpowers the gravitational attraction of the Sun and Moon. Low tides are created by a compensating withdrawal of water from regions around the Earth midway between these two tidal bulges. The alternation of high and low tides is caused by the daily (or *diurnal*) rotation of the solid body of the Earth with respect to these two tidal bulges and the tidal depression. The changing arrival times of any two successive high or low tides at any one location are the result of numerous factors. Fundamental tide producing forces have two components due to the Sun (solar) and the Moon (lunar).

2.1.1.1 Origin of Tide-Producing Forces

It appears to an observer on the Earth that the Moon revolves around the Earth, but in reality the Moon and the Earth each revolve around their common centre of mass known as the *barycentre*. The two astronomical bodies tend to be pulled together by gravitational attraction and simultaneously thrown apart by centrifugal force produced as they revolve around the barycentre. The gravitational attraction and centrifugal force are equal in magnitude and opposite in direction; thus, the Earth and Moon are neither pulled toward each other, nor are they further separated from each other. There is a similar effect for the Earth and Sun system, but they are separate and distinct from those of the Earth and Moon (thus the lunar and solar components).

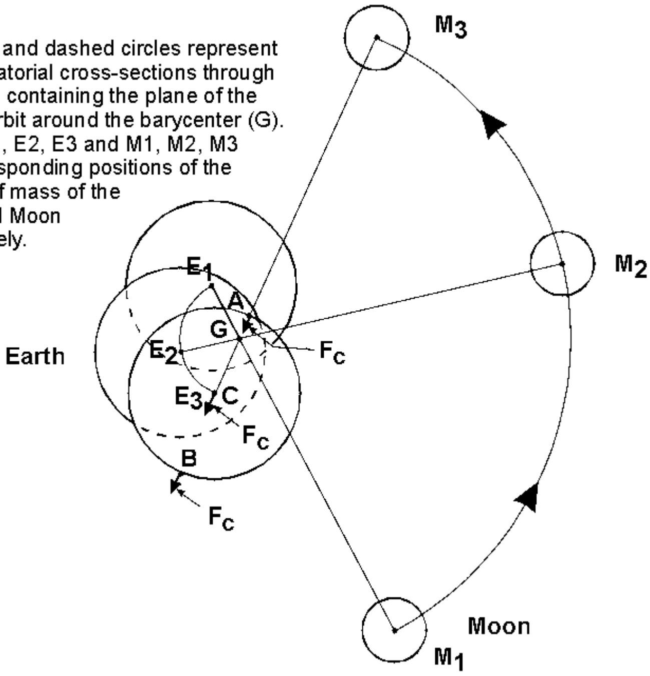
These gravitational and centrifugal forces are balanced only at the centres of mass of the individual bodies. At points on, above or within the bodies, the two forces are not in equilibrium, resulting in tides of the ocean, atmosphere and lithosphere. On the side of the Earth turned toward the Moon or Sun, a net (or *differential*) tide-producing force acts in the direction of the Moon or Sun's gravitational attraction or toward the Moon or Sun. On the side of the Earth directly opposite the Moon or Sun, the net tide-producing force acts in the direction of the greater centrifugal force or away from the Moon or Sun.

2.1.1.2 Centrifugal Force

The barycentre of the Earth/Moon system lies at a point approximately 1,700 km beneath the Earth's surface, on the side toward the Moon, and along a line connecting the individual centres of mass of the Earth and Moon (Figure 5.1). The centre of mass of the Earth describes an orbit (E_1, E_2, E_3...) around the barycentre (G) just as the centre of mass of the Moon describes its own monthly orbit (M_1, $M_{.2}$, M_3...) around this same point.

As the Earth revolves around the barycentre, the centrifugal force produced at the Earth's centre of mass is directed away from the barycentre in the same manner in which an object whirled on a string around one's head exerts a tug upon the restraining hand. Because the centre of mass of the Earth is on the opposite side of the barycentre to the Moon, the centrifugal force produced at the Earth's centre of mass is directed away from the Moon. All points in or on the surface of the Earth experience the same magnitude and direction of this centrifugal force. This fact is indicated by the common direction and length of the arrows representing the centrifugal force (F_c) at points A, B and C in Figure 5.1 and the thin arrows at these same points in Figure 5.2. In a similar fashion, the barycentre of the Earth/Sun system lies at a point well within the Sun because the Sun is so massive relative to the Earth; however the same theory applies.

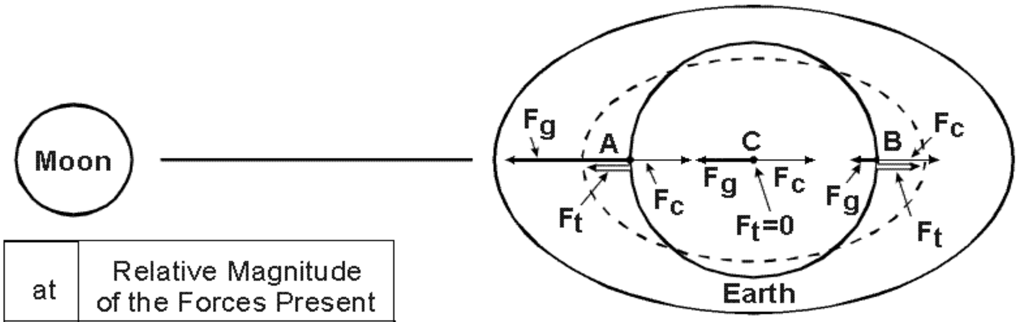
It is important to note that the centrifugal force produced by the daily rotation of the Earth on its own axis is of no consequence in tidal theory. This element plays no part in the creation of the differential tide-producing forces because the force at any particular location remains constant with time, so the water surface is always in equilibrium with respect to it.



The solid and dashed circles represent near-equatorial cross-sections through the earth, containing the plane of the Moon's orbit around the barycenter (G). Points E1, E2, E3 and M1, M2, M3 are corresponding positions of the centers of mass of the Earth and Moon respectively.

Fig. 5.1

Type of Force	Designation
F_c = centrifugal force due to Earth's revolution around the barycenter	thin arrow
F_g = gravitational force due to the Moon	heavy arrow
F_t = the resultant tide-raising force due to the Moon	double shafted arrow



at	Relative Magnitude of the Forces Present
A	$F_g > F_c > F_t$
	$\vee \quad \| \quad \vee$
C	$F_g = F_c > 0$
	$\vee \quad \| \quad \wedge$
B	$F_g < F_c > F_t$

A north-south cross-section through the Earth's center in the plane of the Moon's hour angle; the dashed ellipse represents a profile through the spheroid composing the tidal force envelope; the solid ellipse shows the resulting effect on the Earth's waters.

Fig. 5.2

2.1.1.3 Gravitational Force

While the affect of the external centrifugal force is constant at all points on the Earth, the affect of gravitational force produced by another astronomical body changes from place to place. This is because the magnitude of the gravitational force exerted varies with the distance of the attracting body. Thus, in the theory of tides, another variable influence is introduced, based upon the different distances of various points on the Earth's surface from the Moon's centre of mass. The relative gravitational attraction exerted by the Moon at various positions on the Earth is indicated in Figure 5.2 by arrows labelled F_g which are heavier than those representing the centrifugal force components.

Analogous to the fact that the Earth's own centrifugal force plays no part in producing tides, the effects of the Earth's own gravitational force plays no direct part in the origin of tides. Again, this is because the Earth's gravitational force at any particular location remains constant with time.

2.1.1.4 Differential Tide-Producing Forces

The centrifugal force acting on the centre of the Earth as the result of its revolving around the barycentre is equal and opposite to the gravitational force exerted by the Moon on the centre of the Earth. This is indicated at point C in Figure 5.2 by the thin and heavy arrows of equal length, pointing in opposite directions. The net result of this circumstance is that the tide-producing force (F_t) at the Earth's centre of mass is zero.

The *sublunar point*, point A in Figure 5.2, is approximately 6,400 km nearer to the Moon than point C. Here, the force produced by the Moon's gravitational pull is larger than the gravitational force at C due to the Moon; because the centrifugal force is everywhere equal and opposite to the gravitational pull of the Moon at the Earth's centre of mass, the larger gravitational pull at point A overpowers the centrifugal force, for a net force in the direction of the Moon. This is indicated in Figure 5.2 by the double-shafted arrow. The resulting tide produced on the side of the Earth toward the Moon is known as the *direct tide*.

On the opposite side of the Earth, the *antipodal point*, point B, is about 6,400 km farther from the Moon than point C, the Moon's gravitational force is less than at C; because the centrifugal force at point B is greater than the gravitational attraction of the Moon at point C, the resultant tide-producing force at this point is again directed away from the Earth's centre. This force is indicated by the double-shafted arrow at point B. The tide produced in the antipodal point is known as the *opposite tide*

There is also a similar set up of differential forces in the Earth/Sun system.

2.1.1.5 Tractive Force

Tide-producing forces have a magnitude of only about one 9-millionth of the Earth's own gravitational attraction. The tide-producing forces, therefore, are wholly insufficient to noticeably lift water against the pull of the Earth's gravity. Instead, the tides are generated by the horizontal component of the tide-producing forces. At any point on the Earth's surface, the tide-producing force may be resolved into two components – one vertical, or perpendicular to the Earth's surface, and the other horizontal, or tangential to the Earth's surface; because the horizontal component is not opposed in any way to gravity, it can act to draw particles of water freely over the Earth's surface toward the sublunar and antipodal points.

The horizontal component, known as the tractive ('drawing') component of force, is the actual mechanism for producing the tides. The tractive force is zero at the sublunar and antipodal points, because the tide-producing force is entirely vertical at these points; thus, there is no horizontal component. Any water accumulated in these locations by tractive flow from other points on the Earth's surface tends to remain in a stable configuration, or tidal 'bulge'. Thus, there exists a constant tendency for water to be drawn from other points on the Earth's surface toward the sublunar point (A in Figure 5.2) and its antipodal point (B in Figure 5.2), and to be heaped at these points in two tidal bulges. As a special case of Newton's Universal Law of Gravitation, the tide-producing force varies inversely as the third power of the distance of the centre of mass of the attracting body from a given point on the surface of the Earth.

Within a band around the Earth roughly midway between the sublunar and antipodal points, the tractive force is also zero, because the tide-producing force is directed vertically. There is, therefore, a tendency for the formation of a stable depression in this region.

2.1.1.6 The Tidal Force Envelope

If the ocean waters were to respond exclusively to tractive forces and the Earth were covered with water without continents, the water surface would approximate the shape of a prolate spheroid. The major axis of the spheroid would lie along a line connecting the centres of mass of the Earth and Moon, the minor axis would be centred on, and at right angles to, the major axis. The two tidal humps and the tidal depression are represented in this force envelope by the directions of the major axis and rotated minor axis of the spheroid, respectively. From a purely theoretical point of view, the daily rotation of the solid Earth with respect to these two tidal bulges and the depression may be conceived to be the cause of the lunar tides. With respect to the Sun, the resulting bulges and depressions may be conceived to be the cause of the solar tides.

As the Earth rotates, one would ideally expect to find a high tide followed by a low tide at the same place 6 hours later, then a second high tide after 12 hours, and so forth. This would nearly be the case if a smooth, continent-free Earth were covered to a uniform depth with water, if the tidal force envelope of the Moon alone could be considered, the position of the Moon were fixed and invariable in distance and relative orientation with respect to the Earth and Sun and if there were no other accelerating or retarding influences affecting the motions of the waters of the Earth; however this is far from the actual situation.

First, the tidal force envelope produced by the affect of the Moon is accompanied by, and interacts with, a tidal force envelope produced by the Sun. The tidal force exerted by the Sun is a composite of the Sun's gravitational attraction and the centrifugal force created by the revolution of the Earth around the centre of mass of the Earth-Sun system. The position of this force envelope shifts with the relative orbital position of the Earth with respect to the Sun; due of the great difference between the average distances of the Moon and Sun from the Earth (384,400 km and 150,000,000 km, respectively), the tide-producing force of the Moon is approximately 2.5 times that of the Sun, even though the Sun is so much more massive than the Moon.

Second, there exists a wide range of astronomical variables in the production of the tides. Some of these are the changing distances of the Moon from the Earth and the Earth from the Sun, the angle which the Moon in its orbit makes with the Earth's equator, the angle which the Sun appears in the yearly orbit of the Earth about the Sun and the variable phase relationships of the Moon with respect to the Sun and Earth. Some of the principal types of tides resulting from these purely astronomical influences are described below.

Third, other affects come into play, causing the water level to differ from the astronomically induced tide. These include restrictions to the flow of water caused by the continents and meteorological affects, among others.

2.1.2 Tidal Characteristics

The actual characteristics of the tide at locations around the Earth differ significantly from the idealised tidal envelope discussed previously. First of all, water is a somewhat viscous fluid, which lags in its response to the tide-generating forces. More significantly, the Earth is not a smooth sphere with uniformly deep water covering its entire surface. Tidal movements are affected by friction with the ocean floor and with other ocean currents; the continents interrupt, restrict and reflect tidal movements; the shape and size of the ocean basins accentuate or dampen various components of the tide producing forces.

The rise and fall of the tide does not occur at a uniform rate. From low water, the tide begins rising very slowly at first, but at a constantly increasing rate for about 3 hours when the rate of rise is at a maximum. The rise continues for about 3 more hours, but at a constantly decreasing rate until high water. The falling tide follows a similar pattern of increasing then decreasing rate. When the rise and fall of the tide is represented graphically, it can be seen to approximate the form of a sine curve. At any location, however, the rise and fall of the tide, and consequently the shape of the curve, will be characterised by a variety of features. These features will vary considerably from location to location. Of these features, three may be considered as constituting the principle characteristics of the tide. These three are the time of tide, the range of tide and the type of tide. The hydrographer must understand and consider each of these three characteristics in order to compute and apply tidal reductions to soundings.

2.1.2.1 Time of Tide

A stationary moon would appear to cross the meridian at any given place once every day; but, because the Moon revolves around the Earth in the same direction in which the Earth is rotating, any point on the Earth must actually rotate approximately 12.5° extra each day to catch up with the Moon. This 12.5° requires about 50 minutes, resulting in a ‘tidal day’ of 24 hours and 50 minutes.

The time of tide refers to the time of occurrence of high or low water with respect to the Moon’s meridian passage. This characteristic of the tide at a specific place is described by the high and low water *lunitidal* intervals. The lunitidal interval is the elapsed time between a meridian passage of the Moon and the high or low water. Lunitidal intervals are not constant along any given meridian. The intervals vary, based upon the interruption of the tidal wave by land masses and by the resistance of the ocean floor as the wave moves into shallow water.

Even at any given place, the intervals are not constant, but they do vary periodically within relatively narrow limits. This limited variation in lunitidal interval results from the interaction between the tidal forces of the Moon and the Sun. Between new Moon and first quarter, and between full Moon and third quarter, this interaction can cause an acceleration in tidal arrival times. Between first quarter and full Moon, and between third quarter and new Moon, the interaction can result in a lagging of the tidal arrival.

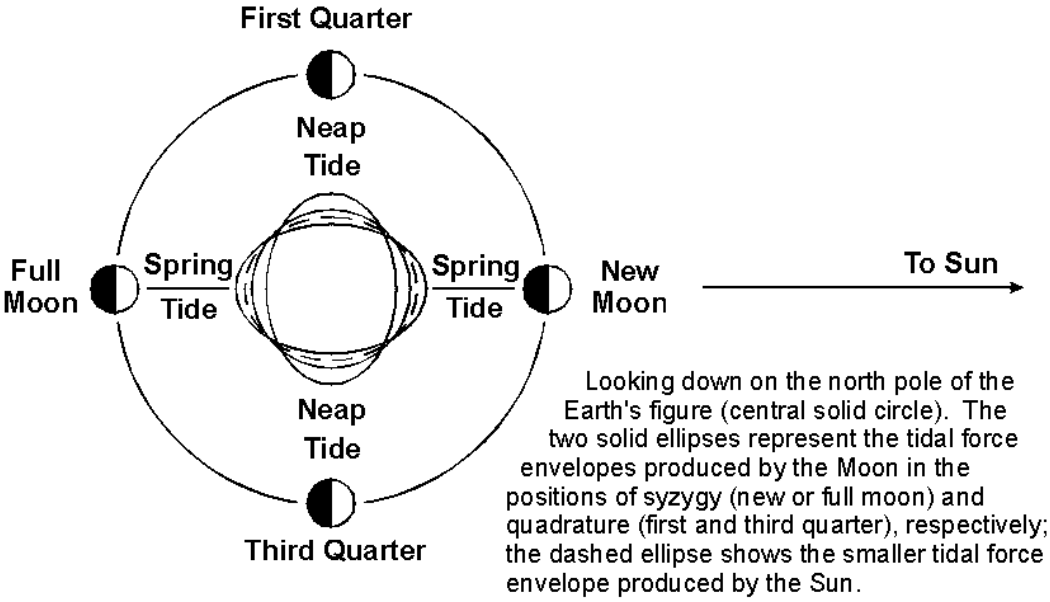
Lunitidal intervals are defined both in terms of the Moon’s meridian passage over Greenwich and the Moon’s meridian passage over the local longitude. They are known respectively as the Greenwich lunitidal interval and the local lunitidal interval. Greenwich intervals are more useful in that they can be used to relate the times of tide at one place to those at any other place. The time of tide is important in analysis and prediction of the tides and in the computation of tidal zoning correctors.

2.1.2.2 Tidal Range

The difference in height between consecutive high and low tides occurring at a given place is known as the range. In the open ocean, the actual height of the tidal wave crest is relatively small (usually 1 m or less) and uniform. It is only when the tidal crests and troughs move into shallow water, against land masses, and into confining channels that large tidal ranges and noticeable variations in range are apparent.

The range of tide at a particular location is not constant, but varies from day to day. Part of this variation is caused by the effects of wind and weather, but mostly it is a periodic phenomenon related to the positions of the Sun and the Moon relative to the Earth. In this day to day change, the tide responds to three variations, each associated with a particular movement of the Moon.

Lunar Phase Effects: Spring and Neap Tides – At most places, the Moon's phase has the greatest affect on the range of the tide. It has been noted that the tides originate from the combined effects of tractive forces generated by both the Sun and the Moon; because of the Moon's changing position with respect to the Earth and Sun (Figure 5.3) during its monthly cycle of phases, tractive forces generated by the Moon and Sun act variously along a common line and at changing angles relative to each other.



Looking down on the north pole of the Earth's figure (central solid circle). The two solid ellipses represent the tidal force envelopes produced by the Moon in the positions of syzygy (new or full moon) and quadrature (first and third quarter), respectively; the dashed ellipse shows the smaller tidal force envelope produced by the Sun.

Fig. 5.3

When the Moon is at new phase and full phase (both positions being called *syzygy*), the gravitational attractions of Moon and Sun act to reinforce each other; as the resultant or combined tidal force is also increased, the high tides are higher than average and low tides are lower. This means the tidal range is greater at all locations which display a consecutive high and low water. Such greater-than-average tides resulting at the syzygy positions of the Moon are known as *spring tides* – a term which merely implies a 'welling-up' of the water and bears no relationship to the season of the year.

At first- and third-quarter phases (*quadrature*) of the Moon, the gravitational attractions of the Moon and Sun upon the waters of the Earth are exerted at right angles to each other. Each force tends in part to counteract the other. In the tidal force envelope representing these combined forces, both the maximum and minimum force values are reduced. High tides are lower than average and low tides are higher. Such tides of diminished range are called *neap* tides, from a Greek word meaning 'scanty'.

Parallax Effects (Moon and Sun) – Since the Moon follows an elliptical path (Figure 5.4), the distance between the Earth and Moon will vary throughout the month by about 50,000 km. The Moon's gravitational attraction for the Earth's waters will change in inverse proportion to the third power of the distance between Earth and Moon, in accordance with the previously mentioned variation of Newton's Law of Gravitation. Once each month, when the Moon is closest to the Earth (*perigee*), the tide-generating forces will be higher than usual, thus producing above-average ranges in the tides. Approximately 2 weeks later, when the Moon (at *apogee*) is farthest from the Earth, the lunar tide-producing force will be smaller and the tidal ranges will be less than average. Similarly, in the Sun-Earth system, when the Earth is closest to the Sun (*perihelion*), about January 2 of each year, the tidal ranges will be enhanced, and when the Earth is farthest from the Sun (*aphelion*), around July 2, the tidal ranges will be reduced.

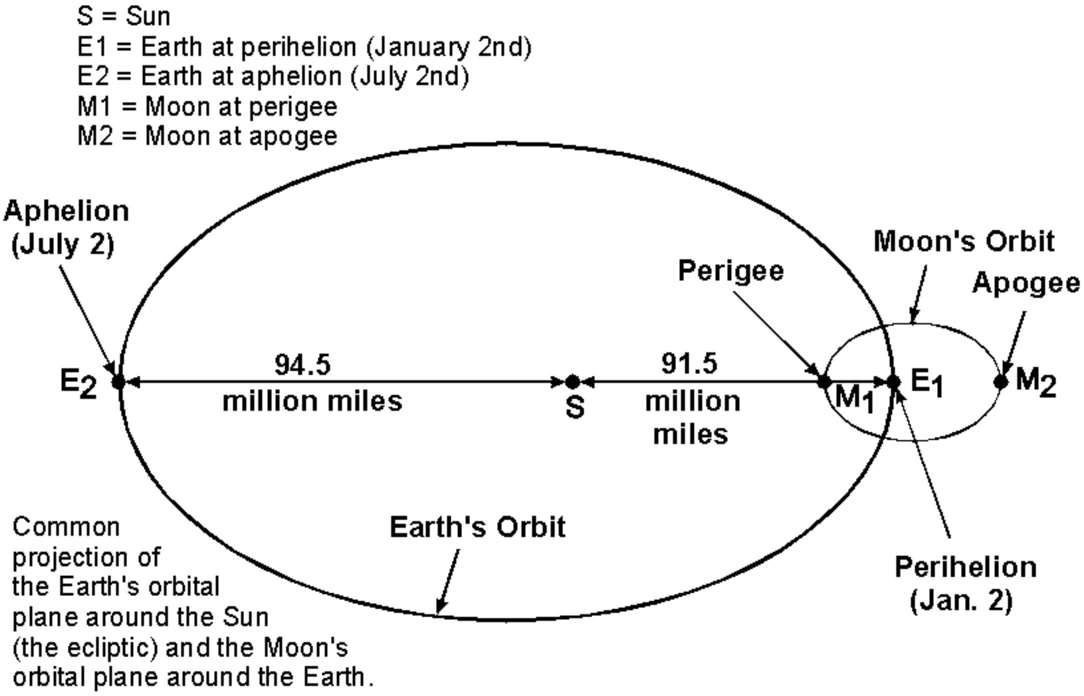


Fig. 5.4

When perigee, perihelion, and either the new or full Moon occur at approximately the same time, considerably increased tidal ranges result. When apogee, aphelion, and the first- or third-quarter Moon coincide at approximately the same time, considerably reduced tidal ranges will normally occur.

Lunar Declination Effects: The Diurnal Inequality – The plane of the Moon's orbit is inclined only about 5° to the plane of the Earth's orbit (the *ecliptic*) and thus the Moon in its monthly revolution around the Earth remains very close to the ecliptic.

The ecliptic is inclined 23.5° to the Earth's equator, north and south of which the Sun appears to move once each half year to produce the seasons. In a similar fashion, the Moon, in making a revolution around the Earth once each month, passes from a position of maximum angular distance north of the equator to a position of maximum angular distance south of the equator during each half month. This is *declination*.

Twice each month, the Moon crosses the equator. In Figure 5.5, this condition is shown by the dashed position of the Moon. The corresponding tidal force envelope due to the Moon is depicted, in profile, by the dashed ellipse. Tides occurring when the Moon is near the equator are known as *equatorial tides*, while those occurring when the Moon is near its maximum northern or southern declination are known as *tropic tides*.

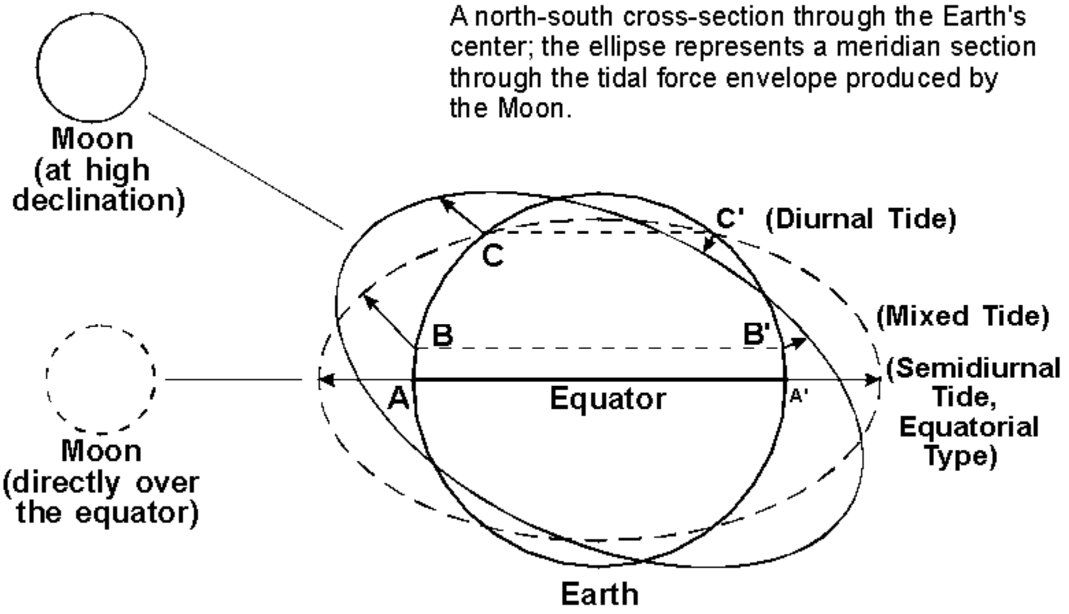


Fig. 5.5

Variability – The effects of phase, parallax and declination are not exhibited everywhere in equal measure, though all three do occur on all parts of the Earth. Phase inequalities are most commonly greatest, but in any particular area any one of the three variations may exert the predominant influence on the range variation of the tide. The month of the Moon's phases, the *synodic month*, is approximately 29.5 days; the month of the Moon' s distance, the *anomalistic month*, is approximately 27.5 days; and the month of the Moon's declination, the *tropic month* is approximately 29.3 days. It follows, therefore, that considerable overall variation in the range of the tide occurs at any place as a result of the progressively changing relations of the three variations to each other. At Seattle, for example, the mean range of tide is about 2.3 m, but individual ranges within a single day may vary from less than 1.5 m to more than 4.5 m.

The range of tide is subject to other periodic variations (for example, the solar parallax differences noted earlier), but the three discussed above are the principal variations. The fact all these major variations cycle completely in 29.5 days or less is the main reason why the hydrographer must operate key tide stations for a minimum of 30 days. Although the variation in range from one 30-day period to another will change somewhat, any 30 consecutive days obtained in combination with long-term stations will usually suffice for preparation of hydrographic tide reductions. One important long-term deviation in range of tide is due to a slowly varying change in orientation of the Moon's orbit called the regression of the Moon's nodes. This variation results in a measurable corresponding slow difference in the range of tide. This deviation gives rise to the need to use nodal factors or nodal corrections when performing harmonic analyses or tide predictions and is important in the determination of various tidal datums (see section 2.1.4).

2.1.2.3 Types of Tide

Of the three principal tidal characteristics, type of tide is the most fundamental. If the tides at two places are of the same type, but differ in time or in range, the tide at one place can be related simply and accurately to the tide at the other location. This similarity underlies the hydrographer's ability to extend sounding datums and compute accurate water-level reducers in areas where a relatively short series of tidal observations have been obtained. On the other hand, if the type of tide at the two places differs, the fact the time or range may be the same does not necessarily indicate a simple relationship between the two places. Differences in time and range of tide are merely differences in degree, but differences in type of tide are differences in the basic nature of the tide.

The type of tide refers to the characteristic form of the rise and fall of the tide as revealed by the tide curve. Although the tide curve for any particular place will differ in some respects from that of any other place, tide curves may be grouped into three large classes or types. These types are semidiurnal, diurnal, and mixed tides.

Referring to Figure 5.5, as the points A and A′ lie along the major axis of this ellipse, the height of the high tide represented at A is the same as that which occurs as this point rotates to position A′ some 12 hours later. When the Moon is over the equator – or at certain other force-equalizing declinations – the two high tides and two low tides on a given day are similar in height at any location. Successive high tides and low tides are then also nearly equally spaced in time and occur uniformly twice daily. This is known as the *semidiurnal* type of tide. A semidiurnal curve of tidal height versus time is shown in the top diagram of Figure 5.6. The semidiurnal type of tide is one in which the full cycle of high and low water is completed in half a day. There are two high and two low waters in each lunar day of 24 hours 50 minutes. To be classified as a semidiurnal tide, the two daily tidal cycles must resemble each other such that, although they are not identical, the two highs do not differ much and the two lows do not differ much.

However, with the changing angular distance of the Moon above or below the equator (as shown in Figure 5.5), the tidal force envelope produced by the Moon is canted, and differences between the heights of two daily tides of the same phase begin to occur. Variations in the heights of the tides resulting from the changes in the declination angle of the Moon and in the corresponding lines of gravitational force action give rise to a phenomenon known as the *diurnal inequality*.

In Figure 5.5, point B is beneath a bulge in the tidal envelope. One-half day later, at point B′, it is again beneath the bulge, but the height of the tide is not as great as at B. This situation gives rise to a twice-daily tide displaying unequal heights in successive high or low waters, or in both pairs of tides. This type of tide, exhibiting a strong diurnal inequality, is known as a *mixed tide*. (See the middle diagram in Figure 5.6.) The mixed type of tide is one in which two highs and two lows occur each day, but in which there are marked differences between the two high waters or between the two low waters of the day. This type of tide is named a mixed tide because it has the properties of a mixture of semidiurnal and diurnal tides.

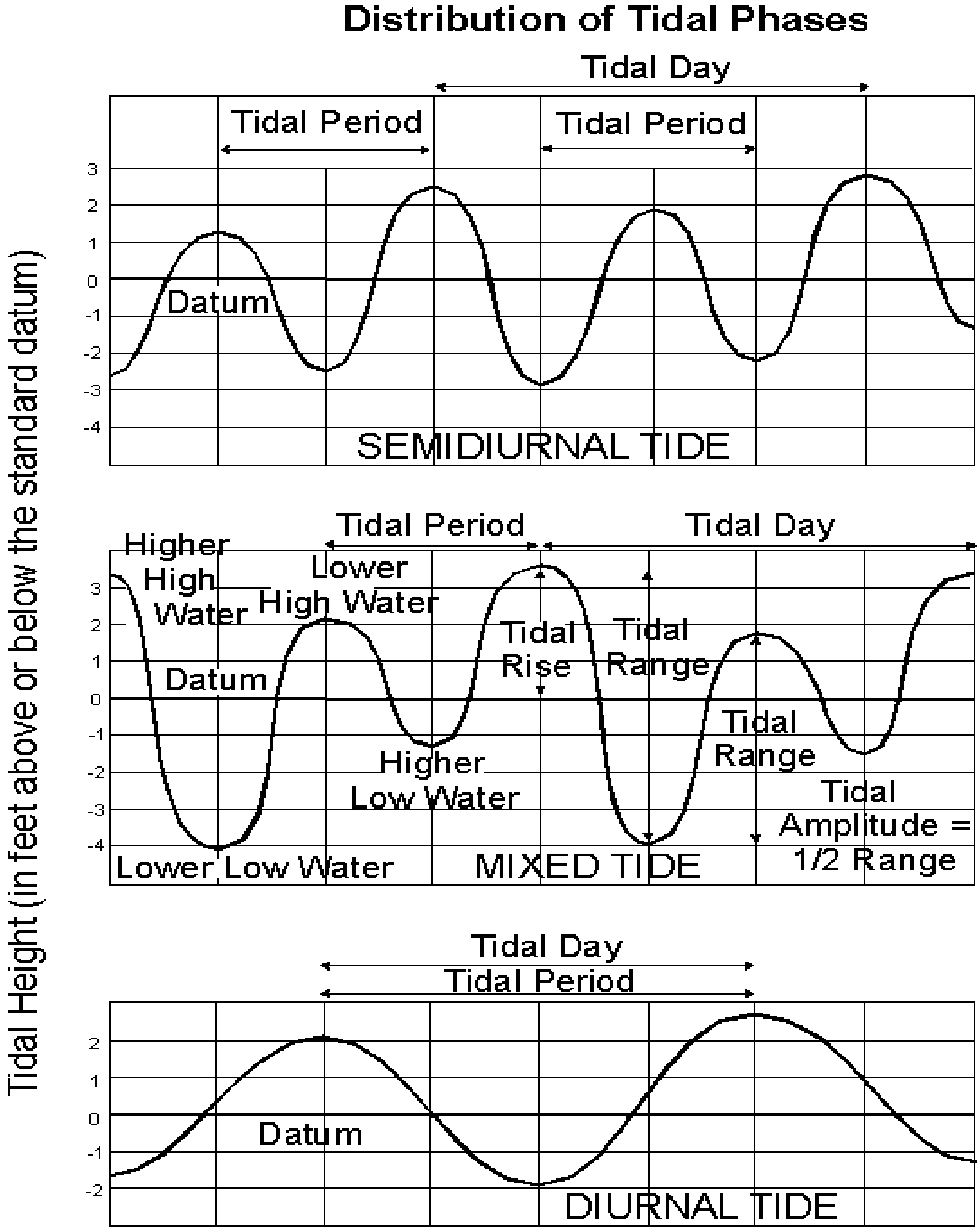


Fig. 5.6

Finally, as depicted in Figure 5.5, the point C is seen to lie beneath a portion of the tidal force envelope. One-half day later, however, as this point rotates to position C′, it is seen to lie above the force envelope. At this location, therefore, the tidal forces present produce only one high water and one low water each day. The resultant diurnal type of tide is shown in the bottom diagram of Figure 5.6. The diurnal type of tide describes those tides in which one high and one low water occur in a lunar day. In this type of tide, the period of the rise, and also of the fall, of tide is approximately 12 hours as opposed to the 6 hour periods of semidiurnal tides.

Examples of each of the three types of tide are shown in Figure 5.6, using three days of tidal records from Hampton Roads, Virginia; San Francisco, California and Pensacola, Florida. The horizontal line through each curve represents the mean level of the sea and the magnitude of the rise and fall of the tide above and below mean sea level is indicated by the scale on the left.

The upper curve, for Hampton Roads, illustrates the semidiurnal type of tide. Two high and two low waters occurred each day, with the morning and evening tides differing relatively little. The bottom curve, for Pensacola, illustrates the diurnal type of tide, one high and one low occurring each day. The curve for San Francisco illustrates one form of the mixed type of tide. Two high and two low waters occurred each day, but the morning tides differ considerably from the afternoon tides. In this particular case, the difference is seen in both the high and low waters.

The difference between corresponding morning and afternoon tides, or diurnal inequality, arises primarily from the fact that the Moon's orbit is inclined to the plane of the equator. This inclination results in the existence of both diurnal and semidiurnal tide producing forces. These forces affect the actual rise and fall of water level to differing degrees in different places, mostly as a result of local and basin response to the forces and thus result in different magnitudes of diurnal inequality. In fact, the distinction between mixed tides and semidiurnal tides is based entirely on this difference in magnitude.

Refer to the tide curve for San Francisco in Figure 5.6, which illustrates a mixed tide. While there is considerable inequality in both the high and low waters, the inequality of the low waters is greater. In Hampton Roads, the inequality, though not very large is exhibited primarily in the high waters. As Figure 5.7 illustrates, the inequality may be featured primarily in the low waters, primarily in the high waters or it may appear equally in the highs and the lows. It is also significant that the diurnal inequality is a feature of the time of tide as well as of the height of tide. Just as the inequality of the height varies from place to place and day to day, the duration of the rise and fall and the lunitidal interval also vary.

To distinguish the two tides of the day, definite names have been given to each of the tides. Of the two highs, the higher is called 'higher high water' (HHW) and the lower, 'lower high water' (LHW). Similarly, the two lows are called 'lower low water' (LLW) and 'higher low water' (HLW). (See Figure 5.6.) As a measure of the inequality, the terms 'diurnal high water inequality' (DHQ) and 'diurnal low water inequality' (DLQ) are used. The DHQ is defined as half the difference between mean higher high water and mean lower high water and the DLQ is defined as half the difference between the means of lower low water and higher low water.

These may be more meaningfully understood as the difference between the mean high water and the mean higher high water, and the difference between the mean low water and the mean lower low water, respectively.

Examination of a month's series of tides, as in the curves shown in Figure 5.7, will show that the diurnal inequality also varies in magnitude in relation to the Moon's declination, the inequality being the least when the Moon is near the equator, as it was in this month from the 3rd to the 5th and the 18th to the 20th, and being the greatest when the Moon is near maximum north or south declination, as it was from the 11th to the 13th and the 25th to the 27th.

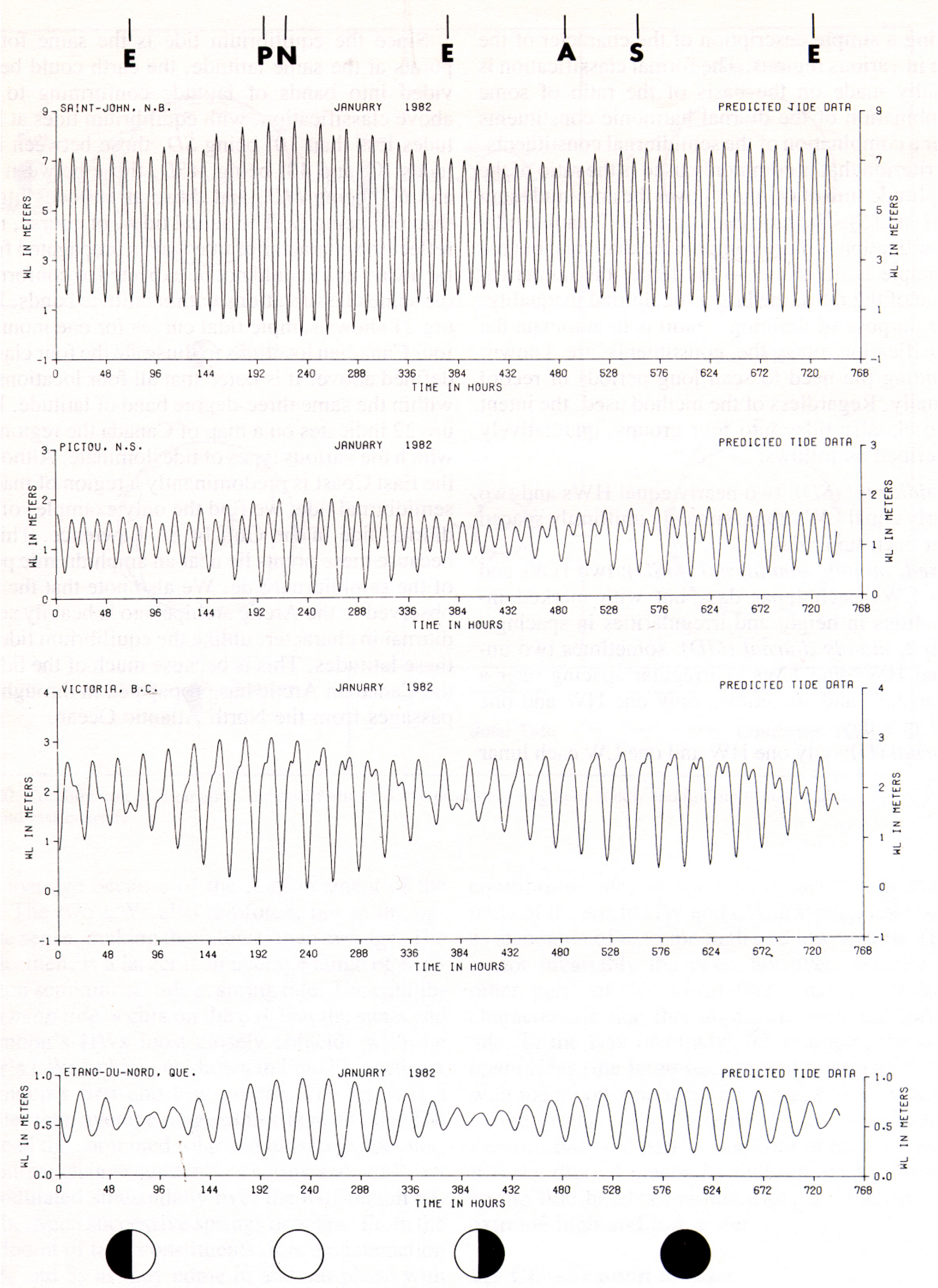

E
PN
E
A
S
E
SAINT-JOHN, N.B.
JANUARY 1982
PREDICTED TIDE DATA
WL IN METERS
TIME IN HOURS
PICTOU, N.S.
JANUARY 1982
PREDICTED TIDE DATA
WL IN METERS
TIME IN HOURS
VICTORIA, B.C.
JANUARY 1982
PREDICTED TIDE DATA
WL IN METERS
TIME IN HOURS
ETANG-DU-NORD, QUE.
JANUARY 1982
PREDICTED TIDE DATA
WL IN METERS
TIME IN HOURS
0
48
96
144
192
240
288
336
384
432
480
528
576
624
672
720
768

Fig. 5.7

2.1.2.4 Basin and Coastal Effects

Although it is the combined forces of the Sun and Moon which set the tidal wave in motion, it is often the size and shape of the ocean basin which controls the characteristics of the tide. For example, Pensacola, Florida is certainly not near the pole – the region to which Figure 5.5 would restrict diurnal tides – but it nonetheless has an unmistakable diurnal tide. Similarly, San Francisco and Hampton Roads are at about the same latitude, but have distinctly different tidal characteristics. Much like the water in a bathtub can be set to surging resonantly from end to end, the tidal oscillations in an ocean basin or a restricted sea can be accentuated by the basin's natural period of resonance. The Pacific Ocean basin accentuates the diurnal component of the tides, resulting in diurnal or strongly mixed tides. The Atlantic, on the other hand, accentuates the semidiurnal component of the tides. As a more localized example, much of the northern Gulf of Mexico responds primarily to the diurnal components of the tide.

The predominate type of tide can change over relatively short distances. For example, the east coast of Florida exhibits semidiurnal tides, most of the west coast of Florida exhibits mixed tides and most of the panhandle of Florida has diurnal tides.

Certain coastal and seafloor configurations can greatly increase the range of tide. Much like a wind wave crests and breaks as it approaches a beach, a tidal wave also increases in height as it encounters shallow water and constricting shoreline. Examination of tidal ranges at coastal stations will almost always show increasing range as the tide moves up a bay or inlet. Cook Inlet, Alaska, a funnel-shaped and shelving body of water, is a particularly good example. As the tide moves in from the Gulf of Alaska, its range increases from about 3 m at the entrance to about 10 m near the head at Anchorage. Above Anchorage, in Turnagain Arm, the inlet narrows and shoals even more. At the times of highest tides, the rising tide flows up the arm against the last of the ebb and rises into a vertical wall of water reaching nearly 2 m high. Such a tidally generated wall of water is known as a *tidal bore*. Tidal bores occur in several rivers or estuaries around the world where the range of tide is great and the configuration of the shore and seabed is ideal.

2.1.3 Non-Tidal Water Level Variations

Changes in the observed water level along the coasts are due not only to tidal forces but are also driven by variety of other forces over a wide-range of time scales. At the highest frequencies, water levels can be affected by tsunamis, seiche and storm surge. Local wind and barometric pressure changes can have a large affect, especially in shallow water. Wind set-up from onshore winds and low barometric pressure will generally cause water levels to be above those predicted while offshore winds and high barometric pressure tend to have the opposite effect. Strong seasonal meteorological patterns will have affects on monthly sea levels. ENSO (El Niño Southerly Oscillation) affects on monthly mean sea levels in the Pacific Ocean are particularly noticeable. Short-term and seasonal affects are also found in tidal estuaries with strong river flows and are driven by run-off characteristics of individual watersheds and controlling dams upstream. The Great Lakes and other large lakes are sensitive to the annual evapo-transpiration cycles and the net gain or loss of water volume. Seasonal variations in oceanic circulation patterns and deviations in ocean eddies also may affect coastal levels. Depending on the spatial scale of the meteorological event, the effects can be seen basin-wide, regionally or only locally. The hydrographer needs to be generally aware of these dependencies in planning and conducting survey operations and to distinguish any anomalies in water level measurements due to weather or natural causes versus gauge malfunction.

2.1.4 Tide and Water Level Datums

The hydrographer must be able to relate all measured depths, regardless of the stage of tide or level of water at the time of sounding, to a common plane or datum. The datum used to reckon heights or depths for marine applications is a vertical datum called a 'water level datum'. For tidally derived datums, most datums are computed over, or referred to, specific 19 year periods or tidal datum epochs. The 19 year period is important as discussed in section 2.1.2.2, because of the 19 year modulation of lunar constituents by the long-term variation in the plane of the Moon's orbit called the regression of the Moon's nodes.

The water level datum to which the soundings on any particular survey are referred is known as the 'sounding datum'. The datum to which depths on a chart are referred is known as the 'chart datum'. A water level datum is called a 'tidal datum' when defined in terms of a certain phase of tide. In United States coastal waters, Mean Lower Low Water (MLLW) is used for both sounding and chart datums. MLLW is computed from tabulation of the observations of the tide, in this case the average of the lower low waters each tidal day over a 19 year period. The United States presently refers all tidal datums computed from tide observations to the 1983-2001 National Tidal Datum Epoch (NTDE) and updates to new NTDEs only after analysis of relative mean sea level change. In contrast, some Chart Datums are derived from harmonic analyses of observations and constructing time series of tide predictions over 19 year periods. The Canadian Chart Datum is the surface of Lower Low Water, Large Tide or LLWLT which encompasses the previously used datum of Lowest Normal Tide (LNT). British Charts now use a Chart Datum of Lowest Astronomical Tide (LAT) based on the lowest predicted tide expected to occur in a 19 year period. LAT is determined at a particular location by performing a harmonic analysis of the observations, then using the resulting harmonic constituents in a prediction equation to predict the elevation of the lowest predicted tide to occur over a 19 year period. Use of LAT has been adopted for international use by the International Hydrographic Organisation (IHO). Harmonic analyses have also been used to determine other Chart Datums. Chart Datums used on some older British Admiralty Charts were Mean Low Water Springs (MLWS) and Indian Spring Low Water (ISLW). MLWS and ISLW are derived from summations of the amplitudes of various major harmonic constituents below local Mean Sea Level.

In areas where there is very little or no tide, other water level datums are used. For the Black Sea, Mean Sea Level or Mean Water level is used. In the Great Lakes, both Canada and the United States use a separate fixed Low Water Datum (LWD) for each lake based on analyses of monthly means during low water stages. In non-tidal lagoons and bays in the coastal United States where the area transitions from tidal to non-tidal, a LWD is used which is determined by subtracting 0.2 m from the local Mean Sea Level derived from observations and adjusted to a 19 year period.

There are a variety of local Chart Datums employed in tidal rivers as well. In the United States, Chart Datums have been derived from analyses of measurements during the low river stages over a period of time and then are held fixed for charting purposes. Examples are the Hudson River Datum and Columbia River Datum derived from MLLW based on observations during the lowest river stages during the year.

The water level datum is a local plane of elevation which applies only in the specific area in which water level measurements have been made. Whether tidal or non-tidal, it is permanently referred to the land by levelling from the water level gauge to a local network of bench marks. Computational procedures for determining tidal datums are addressed later in this Chapter.

Water level datums are completely distinct from geodetic vertical datums. For instance, the United States and Canada use the North American Vertical Datum of 1988 (NAVD 88) and the International Great Lakes Datum of 1985 (IGLD 85) as the vertical datums for geodetic purposes. The relationship between

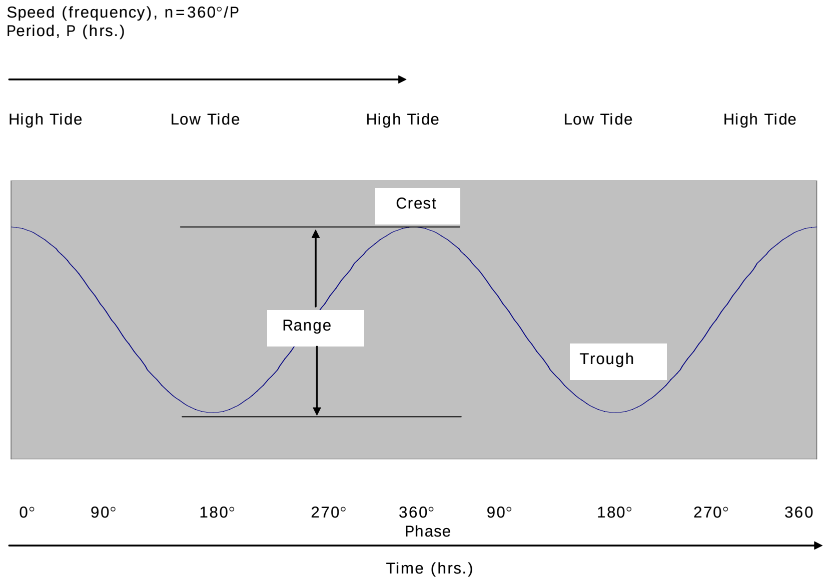
NAVD 88 (or IGLD 85) and local mean sea level or mean water level varies considerably from place to place. In fact, it is impossible to transfer a tidal datum from one place to another with geodetic levelling, without considering local tidal conditions. The geodetic network does, however, establish relationships between the many tide stations and their tidal datum elevations around the North American continent, and it could be used to recover a connected local tidal datum if the tidal bench marks are destroyed. This requires level connections or GPS connections between geodetic and tidal bench mark networks.

2.1.5 Harmonic Analysis and Tide Prediction

Each of the tide-generating motions described in the above sections can be represented by a simple cosine curve as illustrated in Figure 5.8. The horizontal axis represents time and the vertical represents the magnitude of the tide-generating force. The crests give the times of the maximums in the tide-generating force and the troughs, the minimums. For example in Figure 5.8, in the Sun-Earth system, noon, with the Sun overhead, is at the first crest. Six hours later a minimum occurs at the trough. The second maximum is at midnight with the second crest. Another trough is for dawn and then back to the original noon crest.

Each one of the tide-generating motions, represented by a simple harmonic cosine curve, is known as a tidal component, tidal constituent, or harmonic constituent. A letter or letters and usually a subscript are used to designate each constituent. The tidal constituent described above, for example, called the Principal Solar semidiurnal constituent, is designated S_2. The Principal Lunar semidiurnal constituent is designated M_2. S is for sun and M is for moon and the subscript $_2$ means that there are two complete tidal cycles for each astronomic cycle. Thus, these are said to be semidiurnal constituents. Constituents are described by their tidal period (the time from maximum to maximum), **P**. The period for the S_2 is 12.00 solar hours (hr.) and the period for the M_2 is 12.42 solar hours:

$$\text{Speed (frequency), } n = 360°/P$$



From S . Hicks (2004)

Fig. 5.8 "The tide curve visualized as a wave-form"

In tidal work, each constituent (cosine curve) is more often described by its speed (or frequency in degrees per hour). The cosine curve is divided into 360° (from crest to crest). The speed **n** of the constituent is 360°/P. Thus, for S_2, n = 360°/12.00 = 30°/hr; for M_2, n = 360°/12.42 = 28.984°/hr.

There are an infinite number of constituents to describe almost all of the perturbations in the relative motions of the Sun, Moon, and Earth (including the distance and declinational aspects). However, after about 37, the effects of these motions in representing the actual tides are extremely small in most locations in the United States. For tidally complex areas inside estuaries, such as Anchorage, Alaska and Philadelphia, Pennsylvania, it takes over one hundred constituents to adequately describe the tide curve. These additional constituents are artifacts which combine the fundamental diurnal and semidiurnal constituents to produce high frequency (from 3 to 13 cycles per day) constituents which attempt to describe the complex non-linear affects of seabed friction and shallow water.

The representations of the various astronomical events and the development of their periods and speeds are essential in understanding the harmonic analysis techniques. The development of frictional, shallow water and compound tidal constituents are outside of the scope of this chapter.

The Principal Solar semidiurnal constituent, S_2, represents the Earth spinning relative to the Sun. The Earth rotates once in 24 mean solar hours or, since around the world is 360°; it is going at the rate of 360°/24 = 15°/hr. However, there is a maximum in the solar tide producing force under the Sun and again on the opposite side (midnight). So, the period (maximum to maximum) of the constituent is 12 mean solar hours and the speed is: S_2 360°/12 = 30°/hr.

The Principal Lunar semidiurnal constituent, M_2, represents the Earth spinning relative to the Moon. Since the Moon is moving eastward, it takes 24.8412 mean solar hours to bring the Moon back overhead. Again, there are two maximums in this lunar day, so the period is only 12.4206 mean solar hours and its speed is: M_2 360°/12.4206 = 28.984°/hr.

S_2 and M_2 get into phase (maxima lined up) and out of phase (maximum of one lined up with the minimum of the other) to produce spring and neap tides, respectively (Figure 5.3). Spring tides occur at the times of full moon and new moon while neap tides occur at the times of the first and third quarter moons. The revolution of the Moon around the Earth relative to the Sun takes 29.5306 days (called the synodic month or one lunation). Since there are two maximums, spring tides occur every 29.5306/2 = 14.765 days and neap tides 7.383 days later than the springs.

The Larger Lunar Elliptic semidiurnal constituent, N_2, and the Smaller Lunar Elliptic semidiurnal constituent, L_2, are two constituents designed to simulate the cycle of perigee to perigee. These are completely artificial constituents in contrast with S_2 and M_2 which have realistic relationships to the solar and lunar envelopes of the tide-generating forces. Perigee to perigee occurs every 27.5546 days (the anomalistic month) or 661.31 mean solar hours. The speed of perigee to perigee is thus 360°/661.31 = 0.544°/hr. This is a lunar event and the speed of M_2 is 28.984°/hr. The constituent speeds are, therefore:

$$N_2 \quad 28.984 - 0.544 = 28.440°/\text{hr.}$$
$$L_2 \quad 28.984 + 0.544 = 29.528°/\text{ hr.}$$

Thus, when N_2 and L_2 are in phase every 27.5546 days (the anomalistic month) they add to M_2 to simulate the near approach to the Moon (perigee). Also, 13.7773 days later they are out of phase simulating apogee (the Moon farthest away).

The Luni-solar Declinational diurnal constituent, K_1, and the Principal Lunar Declinational diurnal constituent, O_1, are also artificial constituents designed to simulate the cycle of maximum declination to maximum declination of the moon. Maximum north to maximum north occurs every 27.3216 days (the tropical month) or 655.72 mean solar hours. However, both north and south declinations produce the same results. The north to south (and south to north) cycle is 655.72/2 = 327.86 hours. The speed is 360°/327.86 = 1.098°/hr. The speeds of the constituents, as they modify M_2, will be the speed of M_2 plus and minus the speed of the north to south cycle. Since the maximum is only felt once per day as the earth spins, the constituent speeds are half the sum and difference:

K_1 (28.984 + 1.098)/2 = 15.041°/hr.
O_1 (28.984 – 1.098)/2 = 13.943°/hr.

Thus, when K_1 and O_1 are in phase, every 13.6608 days (one half of the tropical month, i.e. the month with respect to the vernal equinox), they add to M_2 to simulate the maximum declination of the Moon north or south. They account for the diurnal inequality due to the Moon (the two high tides and/or the two low tides being unequal in height each tidal day) and, at extremes, diurnal tides (one high tide and one low tide each tidal day).

The Luni-solar Declinational diurnal constituent, K_1, and the Principal Solar Declinational diurnal constituent, P_1, are designed to simulate the cycle of maximum declination to maximum declination of the Sun. Maximum north to maximum north occurs every 365.2422 days (the tropical year) or 8765.81 mean solar hours. However, both north and south declinations produce the same results. The north to south (and south to north) cycle is 8765.81/2 = 4382.91 hrs. The speed is 360°/4382.91 = 0.082°/hr. The speeds of the constituents, as they modify S_2, will be the speed of S_2 plus and minus the speed of the north to south cycle. Since the maximum is only felt once per day as the earth spins, the constituent speeds are half of the sum and difference:

K_1 (30.000 + 0.082)/2 = 15.041°/hr.
P_1 (30.000 – 0.082)/2 = 14.959°/hr.

Thus, when K_1 and P_1 are in phase every 182.62 days (one half of the tropical year, i.e. the year with respect to the vernal equinox), they add to S_2 to simulate the maximum declination of the Sun north or south. These constituents also contribute to diurnal inequality.

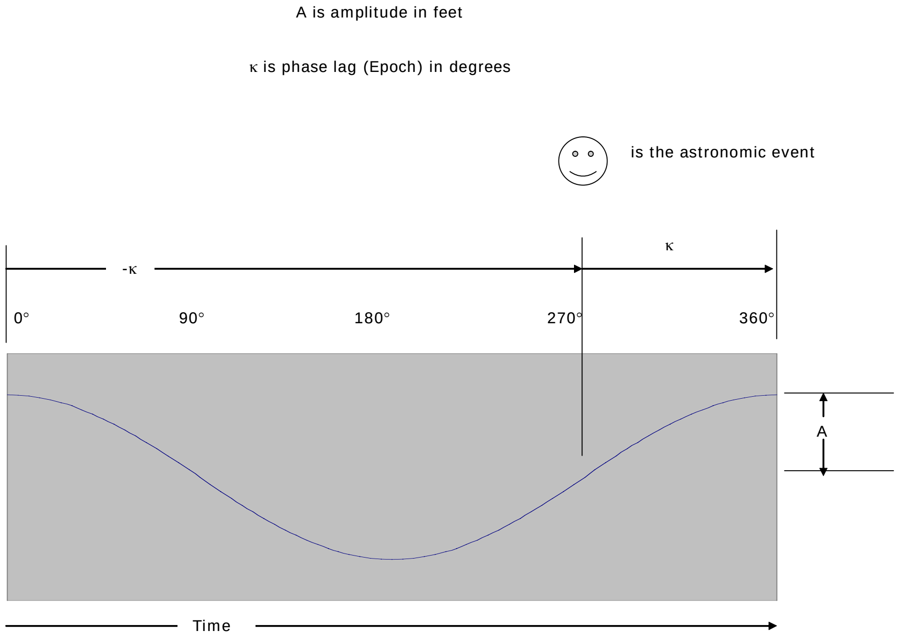
The theoretical relative magnitudes of the various constituents are also of interest. It must be remembered, however, that they are computed from the tide-generating forces and are not necessarily the values in the observed tide. They are based on the value, one, for M_2, since M_2 is usually the dominant constituent. The relative magnitude values, together with the periods of the constituents (360°/speed), are:

M_2	1.00	12.42 hrs.
S_2	0.46	12.00 hrs.
O_1	0.41	25.82 hrs.
K_1	0.40	23.93 hrs.
N_2	0.20	12.66 hrs.
P_1	0.19	24.07 hrs.
L_2	0.03	12.19 hrs.

2.1.5.1 Harmonic Analysis

The mathematical process of looking at one constituent at a time from an observed time series is called harmonic analysis. By knowing the periods of the constituents, it is possible to remove them, providing there is a series which is long enough. Generally, one year is desirable but one month can provide adequate results with dominant semidiurnal tides. Standard analyses are made for 37 constituents by the U.S., although several of them may be quite small at many of the stations.

From a harmonic analysis of the observed water level series, two values are obtained for each tidal constituent. Amplitude, the vertical distance between mean tide level and the level of the crest (when plotted as a cosine curve) is one of the values. The other value is the phase lag (Epoch). The phase lag is the amount of time elapsed from the maximum astronomic event to the first maximum of its corresponding constituent tide. It is usually expressed in degrees of one complete cosine curve (360°) of that constituent. These two values are known as harmonic constants and are illustrated in Figure 5.9. It must be remembered that they are unique to the particular station location from which they were derived. Also, the harmonic constants are treated as a constant even though in the strictest sense they are not because the computed values are affected by noise in the signal, the length of the series analysed, etc. The accepted constants which are used are considered the best estimates of the actual (unknown) values. When any natural event or engineering project occurs, such as erosion, deposition, dredging or breakwater construction, which has the potential to cause major alterations in the adjacent topography new measurements and a new harmonic analysis must be undertaken.



From S. Hicks (2004)

Fig. 5.9 "The amplitude and phase lag of a harmonic constituent"

2.1.5.2 Prediction of Tides

To predict the tide, say for a calendar year, it is necessary to know the harmonic constants (amplitudes and phase lags) for the constituents at each location for which predictions are desired. These are obtained from a harmonic analysis of the observed tide at each station as described above. Adjustments are made for the astronomic configurations for the beginning of the year. Knowing the phase lag of each constituent from the harmonic analysis, the first maximum of each cosine curve occurs after the event by the amount of its phase lag. The amplitude of each cosine curve is that found from the harmonic analysis.

Finally, at each hour of the year, the heights of all the cosine curves are added. When plotted, the resulting curve is normally very similar (in shape and size) to the original observed curve.

The times and heights of the high tides and low tides are placed as predictions for the forthcoming year; the vast number of predictions is possible by applying corrections to those stations for which harmonic constants have been determined - the Primary Control Stations (Reference Stations). Subordinate Stations (those without harmonic constants) are referred to their nearby Reference Stations by empirical constants. Thus, predictions are also obtained for these Subordinate Stations.

The type of tide at a given location is largely a function of the declinations of the Sun and Moon. The declinations are constantly varying such that the type of tide changes throughout the month and year at many of the locations. A more rigorous classification system is available using the amplitudes of the major constituents at each location. Quantitatively, where the ratio of (K_1 + O_1) to (M_2 + S_2) is less than 0.25, the tide is classified as semidiurnal; where the ratio is from 0.25 to 1.5, the tide is mixed mainly semidiurnal; where the ratio is from 1.6 to 3.0, the tide is mixed mainly diurnal; and where the ratio is greater than 3.0, it is diurnal.

The characteristics of diurnal inequality and its fortnightly variation can be explained by considering the combination of diurnal and semidiurnal constituents resulting from the diurnal and semidiurnal tide producing forces. As represented in Figure 5.10, where the semidiurnal constituent is represented by a dotted line and the diurnal constituent by the dashed line, the resultant tide, shown by a solid line, is clearly the sum of the two constituents.

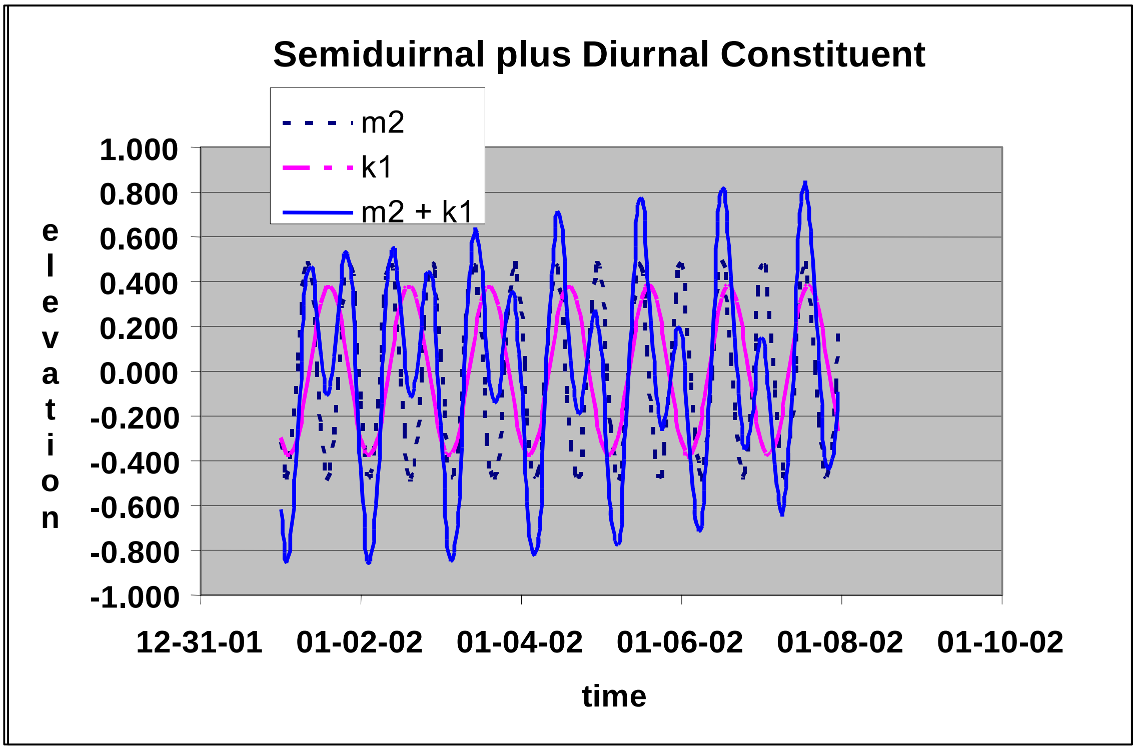


Fig. 5.10

The relative ranges of the constituents at any location, as well as the relative times of the two constituents, depend not only on the relative magnitude and phase of the tide producing forces, but also on the hydrographic characteristics of the tidal basin and the local area. For this reason, the same tide producing forces can result in different relative times and ranges of the diurnal and semidiurnal constituents at different places. Figure 5.10 portrays the simple case where the ranges of the two constituents are equal, but the relative time of the highs and lows varies. In each case, there is considerable diurnal inequality, but there are profound differences in the phase of the tide which exhibits the inequality. In the upper diagram, where the low waters occur at the same time, the diurnal inequality is exhibited in the low waters. In the middle diagram, where the high waters occur simultaneously, the inequality is exhibited in the high waters. And, in the lower diagram, where the two constituents are at mean sea level at the same time, the inequality is featured equally in the highs and the lows. These three diagrams depict the three general classes into which diurnal inequality of tidal heights are grouped.

In actually occurring tides, not only do the times of the constituents have different relations, but the ranges of the two constituents also differ. Refer to the lower diagram in Figure 5.10. If the range of the semidiurnal constituent (dotted line) remains as shown, but the range of the diurnal constituent (dashed line) becomes greater, it can be seen that the lower high water will become lower, and the higher low water will become higher. When the range of the diurnal constituent becomes twice that of the semidiurnal constituent, the lower high water and the higher low water will be equal in height, resulting in a ‘vanishing tide’. As the range of the diurnal constituent increases further, there will be but one high and one low water in a day, a diurnal tide. Combining the affects of time and range, it turns out that if the range of the diurnal constituent is less than 2 times that of the semidiurnal constituent, there will be two high and two low waters daily; if the diurnal range is between 2 and 4 times the semidiurnal there may be two high and two low waters or there may be only one high and one low water in a day; and if the diurnal range exceeds 4 times the semidiurnal, only one high and one low water in the day will occur.

It should be noted that the magnitudes of both diurnal and semidiurnal forces vary during the month, the former being greatest at maximum north and south declination, the latter peaking when the Moon is over the equator. The tide at a given place, therefore, exhibits varying degrees of inequality within any two week period.

In reality, there are over 70 tidal constituents which combine to produce the resultant tide. Of these, there are four major semidiurnal constituents and three major diurnal constituents which are combined into the semidiurnal and diurnal constituents pictured in Figure 5.11.

Each constituent is based on some motion of the Earth, Moon or Sun, or combination thereof. The most important of these constituents complete their cycle within a month and all but the most insignificant complete their cycle within about 18.6 years. The 19 year period of operation required for designation as a primary tide station is based on this timetable. The whole-year period of 19 years is used rather than the 18.6 year cycle, because seasonal variations are often much greater than some of the minor astronomic constituents.

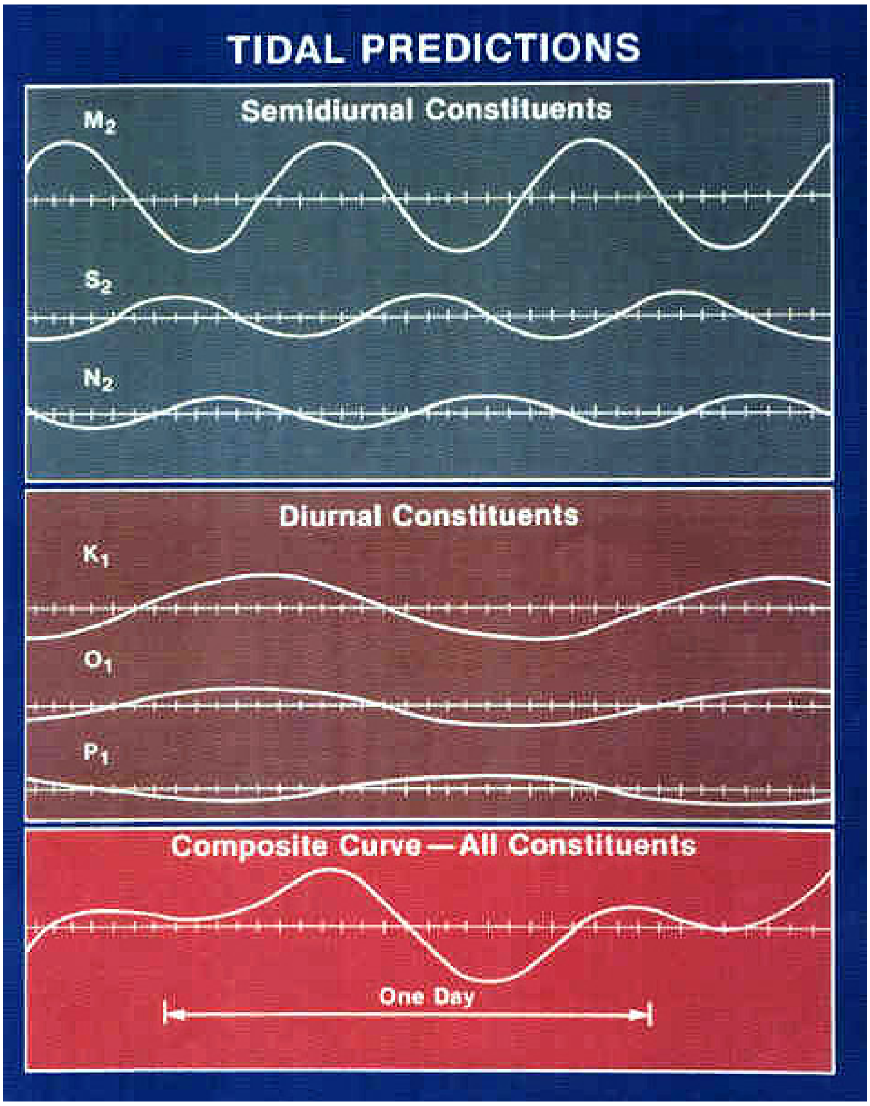


Fig. 5.11

2.2 Operational Support Functions

This section covers the water level and vertical datum requirements for operational support of hydrographic surveys. The scope of this support is comprised of the following functional areas:

a. tide and water level requirement planning;
b. preliminary tide and water level zoning development;
c. control water level station operation;
d. supplemental water level station installation, operation and removal;
e. data quality control, processing, and tabulation;
f. tide and water level datum computation and datum recovery;
g. generation of water level reducers and final tidal zoning.

2.2.1 Error Budget Considerations

The water level reducers can be a significant corrector to soundings to reduce them relative to chart datum particularly in shallow water areas with relatively high ranges of tide. The errors associated with water level reducers are generally not depth dependent, however. The portion of the error of the water level reducers must be balanced against all other sounding errors to ensure that the total sounding error budget is not exceeded. The allowable contribution of the error for tides and water levels to the total survey error budget typically falls between 0.20 m and 0.45 m depending on the complexity of the tides.

The total error of the tides and water levels can be considered to have component errors of:

a. the measurement error of the gauge/sensor and processing error to refer the measurements to station datum. The measurement error, including the dynamic effects, should not exceed 0.10 m at the 95% confidence level (see IHO Standards for Hydrographic Surveys, S-44, April 1998, section 4.2). The processing error also includes interpolation error of the water level at the exact time of the soundings. A estimate for a typical processing error is 0.10 m at the 95% confidence level.

b. the error in computation of first reduction tidal datums and for the adjustment to 19 year periods for short term stations. The shorter the time series, the less accurate the datum, i.e. bigger the error. An inappropriate control station also decreases accuracy. NOAA has determined that the estimated error of an adjusted tidal datum based on one month of data is 0.08 m for the Atlantic and Pacific coasts and 0.11 m for the coast in the Gulf of Mexico (at the 95% confidence level).

c. the error in application of tidal zoning. Tidal zoning is the extrapolation and/or interpolation of tidal characteristics from a known shore point(s) to a desired survey area using time differences and range ratios. The greater the extrapolation/interpolation, the greater the uncertainty and error. Estimates for typical errors associated with tidal zoning are 0.20 m at the 95% confidence level. However, errors for this component can easily exceed 0.20 m if tidal characteristics are very complex, or not well-defined, and if there are pronounced differential effects of meteorology on the water levels across the survey area.

2.2.2 Tide and Water Level Requirement Planning

The planning of tide and water level support for hydrographic surveys requires attention to each of the seven functional areas listed above. In the context of the complete survey operation and generation of output product, the planning involves:

a. determination of overall error budget;
b. study of the tide and water level characteristics and the meteorological and oceanographic environment;
c. determination of which control stations to use and what existing vertical control is in the area, placement, logistics and time period of short-term water level stations and equipment, including GPS and geodetic datum connections;
d. construction of zoning schemes;
e. development of operational data collection, quality control and data processing and analyses functions;
f. development of final zoning and datum determination procedures, application of water level reducers to the hydrographic sheets and estimation of final error budget.

Project planning attempts to minimise and balance these potential sources of errors through the use and specification of accurate reliable water level gauges, optimisation of the mix of zoning required, the number of station locations required and the length of observations required within practical limits of the survey area and survey duration. The practical limits depend upon the tidal characteristics of the area and suitability of the coastline for the installation and operation of appropriate water level gauges.

The hydrographer should plan operations to ensure the collection of continuous and valid data series. Any break in the water level measurement series affects the accuracy of datum computations. Breaks in data also result in increased error in the tide reducers when interpolation is required to provide data at the time of soundings. At a critical measurement site where the water level measurement data cannot be transmitted or monitored during hydrographic operations, an independent backup sensor or a complete redundant water level collection system should be installed and operated during the project.

The locations of tide stations are selected to meet two sets of criteria. First, for adequate coverage, the stations must be sufficient in number and appropriately distributed to accurately portray the tidal or water level regime for the survey area. Second, the specific sites must be suitable for accurate measurement of the full range of water levels experienced.

The density and distribution of tide gauges depends on the changes in water level (usually tidal) characteristics of the survey area. The measurement of tide is generally planned to identify every 0.1 m change in range for areas with 3 m or less range, every 0.2 m change in range for areas with more than 3 m of range and to identify every 0.3 hour change in Greenwich interval.

In determining coverage requirements, tidal characteristics are first evaluated in a general geographic sense. The type of tide and changes in the type (semidiurnal, diurnal, or mixed) are analysed. The source from which the tide advances into the area is determined and the strength of the tide is evaluated relative to seasonal and localised meteorological influences. The areas of transition from tidal to non-tidal regimes are particularly important, since non-tidal areas receive different treatment for low water datum determination.

Next, the tidal characteristics are evaluated in a localised geographical context. Complex changes occur to the tide across shallow inlets, extensive marshes and narrow constrictions. Lagoons may cut off tidal flow at low water and constant river flow affects the tide at all stages. In large bays of comparatively shallow depth having a small range of tide, the wind has considerable affect on the time and height of tide. This is also true in broad stretches of rivers or along shores where the water is shoal. Man-made influences such as bulkheads, dredging, dams, levees, hydroelectric intakes and water level management practices can have significant impacts.

After this analysis, approximate station locations are identified. Stations are usually required on both sides of any significant impediments to tidal flow; at frequent intervals in very shoal areas and in the narrow upper reaches of tidal rivers; at the head of navigation or limit of survey of all rivers and streams; and on both sides of transitions from tidal to non-tidal or between diurnal, mixed, and semidiurnal tides. The survey area is usually bracketed with stations so that extrapolation of water level reducers is not required. When surveying exposed channel approaches where depths are not much greater than the draft of vessels, the water level data provided by an inshore gauge alone may not be accurate enough for the reduction of soundings. In such surveys, a temporary station on an offshore structure may be very desirable. Also, overlapping coverage is normally planned, so that at least two stations are operating for any given portion of the survey area. This overlap aids interpolation for zoning purposes and provides some backup data should one gauge malfunction.

In many cases, historical information is available to assist in planning water level coverage. Primary and secondary station information, as well as tide and water level data from previous hydrographic surveys, provide good indications as to how many and approximately where tide stations may be required for a new survey. Where historical information is not available, the planner must estimate the requirements by analysing data for nearby areas with similar physiographic characteristics. In these situations, it is prudent to err on the side of too many stations rather than being unable to provide satisfactory control for the entire survey area. Soundings acquired with insufficient tide control cannot be corrected with data from gauges installed after the survey.

2.2.3 Preliminary Tide and Water Level Zoning

Tide and water level zoning is a tool used to extrapolate or interpolate the tide or water level variations from the closest water level station to the survey area. In many instances, interpolation or extrapolation is not necessary and water level reducers are provided directly from the water level gauge referenced to Chart Datum. In most cases, existing stations are not near the survey area or not enough water level stations can be installed in a practical sense to provide direct control everywhere. The estimated errors in the extrapolation and interpolation of water levels must be balanced with the total error budget. The more stations which can be established throughout a survey area, the less the zoning error. The more stations required, the higher the cost and logistical complexity of operations.

Any zoning scheme requires an oceanographic study of the water level variations in the survey area. For tidal areas, co-tidal maps of the time and range of tide are constructed based on historical data, hydrodynamic models and other information sources. Based on how fast the time and range of tide progress through a given survey area, the co-tidal lines are used to delineate discrete geospatial zones of equal time and range of tide. Once this is constructed, time and range correctors to appropriate operational stations or tide prediction stations can be calculated.

The techniques described above will provide correctors in the immediate vicinity of a tide station. In many instances, the survey area will fall between two or more tide stations, each of which has a different range of tide. In such situations, the correctors for the intermediate area must be interpolated into correction zones from the surrounding stations. In most cases, the zoning provided with predicted tides will be adequate for this purpose. However, should predicted zoning be unavailable or proved incorrect, the hydrographer can prepare co-tidal and co-range charts in the field from preliminary observed water levels.

A co-tidal chart portrays lines of equal Greenwich lunitidal intervals. For zoning in the field, co-tidal charts are usually drawn to show lines of equal time of high or low water before or after the relevant time at a reference tide station.

Co-range charts portray lines of equal tidal range. For field use, the lines are usually labelled with ratios relative to the reference station. These relationships to the reference gauge facilitate the preparation of reducers in the manner. Figures 5.12 and 5.13 are examples of co-tidal and co-range charts of a hypothetical bay in which a survey is conducted.

Pt. I TIDES

CONSTRUCTING A CO-TIDAL CHART-TIME CURVES

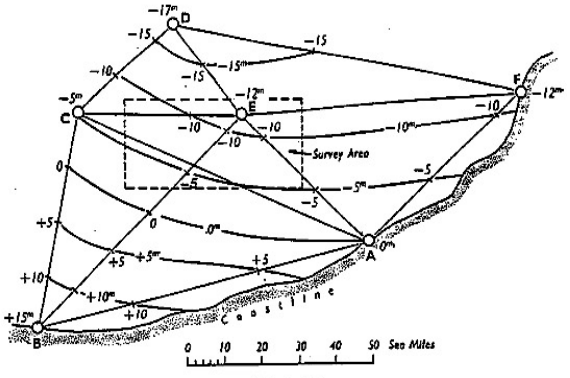


Fig. 2-16a

CONSTRUCTING A CO-TIDAL CHART-RANGE CURVES

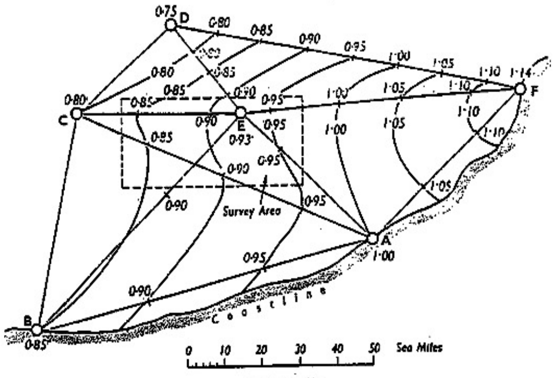


Fig. 2-16b

37

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Fig. 5.12 and 5.13

Co-tidal chart – Co-tidal charts are generally constructed using GIS drawing tools. The following is a simple manual example to illustrate some of the fundamentals. To construct a co-tidal chart, the hydrographer should plot the reference station and all secondary, tertiary and short-term tide stations in the survey area. For best results, the survey area should be within a nearly equilateral triangle or a quadrilateral formed by tide stations. For each station, the time of arrival of high or low water before or after the time of arrival at the reference station is annotated. In some cases, the time differences are the same for high and low water.

For simplicity, such a case is depicted in Figure 5.12. In many cases, however, separate co-tidal charts for high and low waters are required. Adjacent and opposite stations are connected by straight lines. Periodic intervals along each line are then interpolated and marked. The time segments used depend upon the range of tide and the precision desired for reducers. For most areas, 10 min is a suitable interval to select. The corresponding interval marks along each line are connected by a smooth curve as shown in Figure 5.12. When two interpolated points conflict, precedence is given to the mark along the shorter line and to the marks on lines which the curves intersect closest to perpendicularity. In many instances, the survey areas are so complex that drawing of interpolation lines connecting stations is not practical and the co-tidal lines are placed by the oceanographer using GIS tools.

Co-range Charts – As shown in Figure 5.13, the chart is laid out as for the co-tidal chart. Instead of times, tidal ranges or range ratios to the reference station are annotated. Each connecting line is interpolated by increments, usually 0.1 m of range or the equivalent ratio increment. Smooth co-range lines are then drawn through the corresponding points on each line, giving precedence in the same manner as on co-tidal lines.

Zoning Charts – The zoning chart is constructed by overlaying the co-tidal chart on the co-range chart. The hydrographer can then select regions in which to apply range and time correctors to the reference station height and time. Examination of Figures 5.12 and 5.13 will reveal that the co-tidal lines and the co-range lines are not parallel. This difference in orientation is typical of most areas and often results in irregular shaped corrector zones which may not be operationally efficient. For the purposes of simplifying preliminary field correctors, however, the hydrographer can adjust the size and shape of zones to accommodate the operational situation. For example, if a sounding system of east-west lines were planned, it might be most efficient to alter the zones into east-west bands across the bay. It becomes a matter of judgment in balancing operational considerations against the need for accuracy and precision. Regardless of the zoning selected by the hydrographer in the field, however, final zoning will be based on a complete analysis of the observed water levels and will be designed for maximum accuracy.

Offshore Zoning – When it is impossible, as it is for offshore soundings, to bracket a survey area with tide stations, water-level zones must be selected on more theoretical considerations. Where the continental shelf is broad and the tidal wave approaches parallel to the shore, as it does on much of the east coast of the United States, the tide will arrive offshore earlier than inshore. On other coasts, such as the west coast of the United States, the tide wave is nearly perpendicular to shore with minimal time and range differences offshore. For offshore sounding reducers, estimates of time and range corrections to be applied to coastal tide stations may be made from existing co-tidal charts or from existing ocean tide models.

2.2.4 Control Water Level Station Operation

Control water level stations are those which already have accepted datums computed for them and which are typically in operation during the survey. They may be operated by the agency or country performing the survey or maintained by another entity. These control stations are typically used as references for tidal prediction, as direct sources of water level reducers during survey operations, as a control data source to which zoning correctors are applied and control for simultaneous comparison with short-term stations for datum recovery or datum determination. These long-term control stations are usually part of each nation's national network of tide and water level stations.

2.2.5 Supplemental Water Level Station Requirements

These stations are used to provide time series data during survey operations, tidal datum references and tidal zoning which all factor into the production of final water level reducers for specific survey areas. Station locations and requirements may be modified after station reconnaissance or as survey operations progress.

The duration of continuous data acquisition should be a 30 day minimum except for zoning gauges. Data acquisition is from at least 4 hours before the beginning of the hydrographic survey operations to 4 hours after the ending of hydrographic survey operations and/or shoreline verification in the applicable areas. Stations identified as '30 day' stations are the 'main' subordinate stations for datum establishment, providing tide reducers for a given project and for harmonic analysis from which harmonic constants for tide prediction can be derived. At these stations, data must be collected throughout the entire survey period in specified areas for which they are required and not less than 30 continuous days are required for accurate tidal datum determination. Additionally, supplemental and/or back-up gauges may also be necessary based upon the complexity of the hydrodynamics and/or the severity of environmental conditions of the project area.

A complete supplemental water level measurement station installation shall consist of the following:

a. the installation of the water level measurement system [water level sensor(s), ancillary measurements sensors (if required), a Data Collection Platform (DCP) or data logger and satellite transmitter (if installed)] and supporting structure for the DCP and sensor, and a tide staff (if required).

b. the recovery and/or installation of a minimum number of bench marks and a level connection between the bench marks and the water level sensor(s) and tide staff as appropriate on installation and removal of the gauges. Static GPS measurements should also be made to a subset of the bench marks.

2.2.5.1 Water Level Measurement Systems

2.2.5.1.1 Water Level Sensor and Data Collection Platform

Various types of water level sensors and station configurations are possible. There are several types of water level sensors which are used by various countries for support of hydrographic surveys. The U.S. uses air acoustic and pressure (vented) digital bubbler systems for control and supplemental station in tidal areas and float driven shaft angle encoders for the Great Lakes control stations, see Figure 5.14. Many other types of float driven and internal non-vented pressure systems are deployed around the globe.

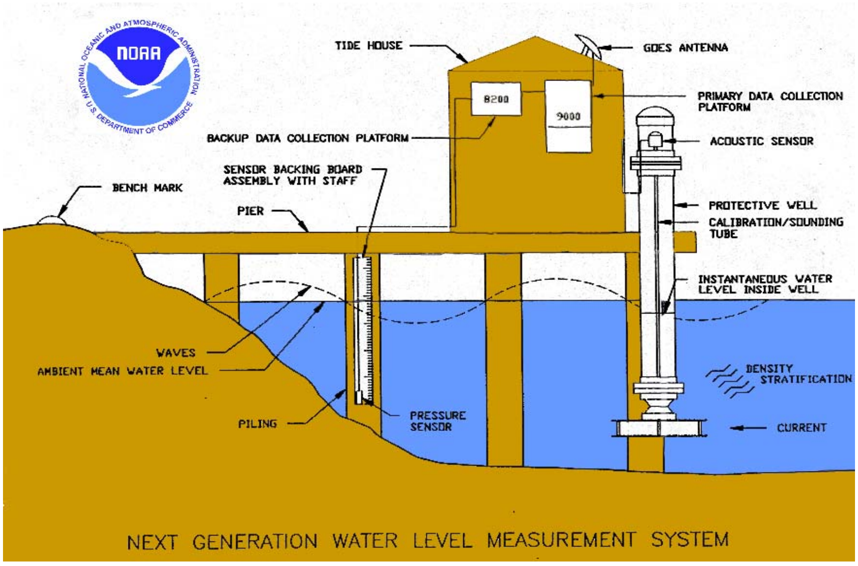


Fig. 5.14

The sensor measurement range should be greater than the expected range of water level. Gauge/sensor systems should be calibrated prior to deployment and the calibration should be checked after removal from operations. The calibration standard's accuracy must be traceable to some national or international standard. The required water level sensor resolution is a function of the tidal range of the area in which hydrographic surveys are planned. For tidal range less than or equal to 5 m, the required water level sensor resolution should be 1 mm or better; for tidal range between 5 m and 10 m, the required water level sensor resolution should be 3 mm or better; and for tidal range greater than 10 m, the required water level sensor resolution should be 5 mm or better.

The data acquisition systems should acquire and store water level measurements at time steps required for tabulation of the significant variations in the water levels. For tides, the U.S. uses a 6 minutes interval to ensure tabulation of high and low tides to the nearest tenth of an hour. Other longer sampling intervals may be appropriate for lakes and non-tidal areas, although the sampling interval should be short enough to measure any seiche action. Many sensors employ burst sampling at high rates to provide a data point at the sampling or reporting interval. NOAA systems use a 3 minute average of higher rate samples from the sensors to derive the 6 minute interval data points. Sample statistical outliers and standard deviations are then used as quality control parameters. Water level data loggers should have a clock accuracy of within one minute per month. Known error sources for each sensor shall be handled appropriately through ancillary measurements and/or correction algorithms. Examples of such errors are water density variations for pressure gauges, barometric pressure correction for non-vented systems, sound path air temperature differences for acoustic systems and high frequency wave action and high velocity currents for all sensor types.

For tidal datum applications, it is important for gauges and sensors to be carefully maintained with either frequent calibration checks or cycled swaps of calibrated sensors for long-term installations. The sensor 'zero' must be precisely related to either a tide staff and/or the bench marks through staff/gauge comparisons or direct levelling between the sensor and the bench marks. Vertical stability of the sensor 'zero', both physically and internally, must be monitored and any movement taken into account in the data reduction and datum computation.

The hydrographer should install a tide staff at a station if the reference measurement point of a sensor (zero of a gauge) cannot be directly levelled to the local bench marks, i.e. orifice is laid over sea floor in case of pressure based bubbler gauges. Even if a pressure gauge can be levelled directly, staff readings are still required for assessment of variations in gauge performance due to density variations in the water column over time. The tide staff should be mounted independent of the water level sensor so that stability of the staff or sensor is maintained. Staff should not be mounted to the same pile on which the water level sensor is located. The staff should be plumbed. When two or more staff scales are joined to form a long staff, the hydrographer should take extra care to ensure the accuracy of the staff throughout its length. The distance between staff zero and the rod stop should be measured before the staff is installed and after it is removed and the rod stop above staff zero height should be reported on the documentation forms.

2.2.5.1.2 Tide Staffs

In areas of large tidal range and long sloping beaches (i.e. Cook Inlet and the Gulf of Maine), the installation and maintenance of tide staffs can be extremely difficult and costly. In these cases, the physical installation of a tide staff(s) may be substituted by systematic levelling to the water's edge from the closest bench mark. The bench mark becomes the "staff stop" and the elevation difference to the water's edge becomes the "staff reading".

When using pressure sensors, for instance, a series of gauge/staff comparisons through a significant portion of a tidal cycle should be required at the start, at frequent intervals during deployment and at the end of a deployment. The staff to gauge observations at the start and end of deployment should be at least each three hours long and the periodic observations during the deployment should be 1 hour long.

In general, the gauge and staff should be read simultaneously and recorded once a day (minimum of three days in each seven day period) for the duration of the water level measurements. The average staff-to-gauge difference should be applied to water level measurements to relate the data to staff zero. Frequent gauge/staff comparisons (at least three times per week or minimum eight times per month) during deployment should be required to assist in assuring measurement stability and minimising processing type errors. A higher number of independent staff readings decrease the uncertainty in transferring the measurements to station datum and the bench marks. If logistically, it is not practical to have a local tide observer or for the field party to visit the station because the survey area is a long distance from the station, then whenever visits are made, a 'burst' sample of several staff readings should be made over a few hours time period instead of one discrete reading.

If the old staff is found destroyed by elements during the deployment, then a new staff should be installed for the remainder period of the deployment and a new staff to gauge constant needs to be derived by new sets of staff to gauge observations.

2.2.5.1.3 Bench Marks and Levelling

A network of bench marks is an integral part of every water level measurement station. A bench mark is a fixed physical object or marker (monumentation) set for stability and used as a reference to the vertical and/or horizontal datums. Bench marks in the vicinity of a water level measurement station are used as the reference for the local tidal datums derived from the water level data. The relationship between the bench marks and the water level sensor or tide staff are established by differential levelling. Since gauge measurements are referenced to the bench marks, it follows that the overall quality of the datums is partly dependent on both the quality of the bench mark installation and the quality of the levelling between the bench marks and the gauge.

2.2.5.1.4 Number and Type of Bench Marks

The number and type of bench marks required depends on the duration of the water level measurements. Each station typically has one bench mark designated as the primary bench mark (PBM), which should be levelled to on every run. The PBM is typically the most stable mark in close proximity to the water level measurement station. The most desirable bench mark for GPS observations will have from 10° above the horizon 360° of horizontal clearance around the mark. If the PBM is determined to be unstable, another mark should be designated as PBM. The date of change and the elevation difference between the old and new PBM should be documented. For stations installed for longer than one-month, from 3 to 5 bench marks should be established or recovered and levelled to for each station.

2.2.5.1.5 Levelling

At least third-order levels should be run at short-term subordinate stations operated for less than one-year. Levels should be run between the water level sensor(s) or tide staff and the required number of bench marks when the water level measurement station is installed, modified (i.e. water level sensor serviced or replaced), for bracketing purposes or prior to removal. In any case, levels are required at a maximum interval of six months during the station's operation and are recommended after severe storms, hurricanes, earthquakes to document stability (see stability discussed below).

Bracketing levels to appropriate number of marks (five for 30-day minimum stations) are required if smooth tides are required 30 days or more prior to the planned removal of a applicable gauge(s) or after 6 months for stations collecting data for long term hydrographic projects.

2.2.5.1.6 Stability

If there is an unresolved movement of the water level sensor or tide staff zero relative to the PBM, from one levelling to the next, of greater than 0.010 m, the hydrographer should verify the apparent movement by re-running the levels between the sensor zero or tide staff to the PBM. This threshold of 0.010 m should not be confused with the closure tolerances used for the order and class of levelling.

2.2.5.1.7 GPS Observations at Bench Marks

Static GPS surveys should be conducted on a minimum of one bench mark, preferably two marks if time and resources permit, at each subordinate water level station installed/occupied for hydrography. Static GPS surveys should be conducted at water level stations concurrently with the occupation of NAVD 88 marks, if possible, to accomplish water level datum transfers using GPS-derived orthometric heights.

High accuracy static differential GPS surveys require a geodetic quality, dual frequency, full-wavelength GPS receiver with a minimum of 10 channels for tracking GPS satellites. A choke ring antenna is preferred, however, any geodetic quality ground plane antenna may be used. More important than antenna type, i.e. choke ring or ground plane, is that the same antennas or identical antennas should be used during the entire observing sessions. If not, a correction for the difference in antenna phase patterns (modelled phase patterns) must be applied. This is extremely critical for obtaining precise vertical results. The antenna cable length between the antenna and receiver should be kept to a minimum when possible; 10 meters is the typical antenna cable length. If a longer antenna cable is required, the cable must be fabricated from low loss coaxial cable (RG233 for up to 30 meters and RG214 over 30 meters).

The most desirable bench mark for GPS observations will have from 10° above the horizon 360° of horizontal clearance around the mark. Newly established marks should be set in locations which have the required clearances, if at all possible.

Meteorological data (air temperature, barometric pressure and relative humidity) need to be collected, if available, during the GPS observations. Meteorological data should be collected at or near the antenna phase centre. All equipment should be checked for proper calibration periodically.

2.2.5.2 Station Documentation

The documentation package:

a. installation of a station;
b. performance of bracketing levels;
c. gauge maintenance and repair;
d. removal of the station.

The station documentation generally includes, but is not limited to the following:

a. calibration test documentation from an independent source other than the manufacturer for each sensor used to collect water level or ancillary data;

b. a station report documenting the station configuration information and related metadata;

c. new or updated nautical chart section or equivalent map indicating the exact location of the station, with chart number or map name and scale shown;

d. large-scale sketch of the station site and digital GIS compatible file provided on diskette showing the relative location of the water level gauge, staff (if any), bench marks and major reference objects found in the bench mark descriptions. The sketch should include an arrow indicating north direction, a title block, latitude and longitude (derived from handheld GPS) of the gauge and all bench marks;

e. new or updated description of how to reach the station from a major geographical landmark;

f. photographs of station components and bench marks. Digital photographs are preferred. As a minimum, photographs should show a view of the water level measurement system as installed, including sensors and gauge housing; a front view of the staff (if any); multiple views of the surroundings and other views necessary to document the location; photographs of each bench mark, including a location view and a close-up showing the bench mark stamping. All photographs should be annotated and referenced with the station name, number, location and date of the photograph;

g. description/recovery notes of bench mark;

h. level records and level abstract, including level equipment information;

i. datum offset computation worksheet or Staff/Gauge difference work sheet as appropriate showing how sensor ‘zero’ is referenced to the bench marks.

2.2.6 Data Processing and Tabulation

2.2.6.1 Data Quality Control

The required output product used in generation of tide reducers and for tidal datum determination is a continuous time series of discrete interval water level data for the desired time period of hydrography and for a specified minimum time period from which to derive tidal datums. (Note: this discrete time interval is typically 6 to 10 minutes but for discussion purposes, 6 minutes will be used.) The 6 minute interval water level data from the water level gauges should be quality controlled for invalid and suspect data as a final review prior to product generation and application. This includes checking for data gaps, data discontinuities, datum shifts, anomalous data points, data points outside of expected tolerances such as expected maximum and minimum values and for anomalous trends in the elevations due to sensor drift or vertical movement of the tide station components and bench marks.

Quality control should include comparisons with simultaneous data from backup gauges, predicted tides or data from nearby stations, as appropriate. Data editing and gap filling should use documented mathematically sound algorithms and procedures and an audit trail should be used to track all changes and edits to observed data. All inferred data should be appropriately flagged. Water level measurements from each station should be related to a single, common datum, referred to as Station Datum. Station Datum is an arbitrary datum and should not be confused with a tidal datum such as MLLW. All discontinuities, jumps or other changes in the gauge record (refer to the specific gauge user’s guide) which may be due to vertical movement of any one of the gauge, staff, or bench marks should be fully documented. To avoid confusion all data should be recorded on UTC (Co-ordinated Universal Time – also known as Greenwich

Mean Time - GMT) and the units of measurement should be properly denoted on all hard-copy output and digital files.

2.2.6.2 Data Processing and Tabulation of the Tide

The continuous 6 minute interval water level data are used to generate the standard tabulation output products. These products include the times and heights of the high and low waters, hourly heights, maximum and minimum monthly water levels and monthly mean values for the desired parameters. Examples of these tabulation products are found in Figure 5.15 for tide stations. The times and heights of the high and low waters should be derived from appropriate curve-fitting of the 6 minute interval data. For purposes of tabulation of the high and low tides and not non-tidal high frequency noise, successive high and low tides should not be tabulated unless they are appropriately derived. Hourly heights should be derived from every 6 minute value observed on the hour. Monthly mean sea level and monthly mean water level should be computed from the average of the hourly heights over each calendar month of data. Data should be tabulated relative to a documented consistent station datum such as tide staff zero, arbitrary station datum, MLLW, etc. over the duration of the data observations. Descriptions of general procedures used in tabulation are also found in the Tide and Current Glossary, Manual of Tide Observations and Tidal Datum Planes.

2.2.6.3 Data Editing and Gap Filling Specifications

When backup sensor data are not available, data gaps in 6 minute data should not be filled if the gaps are greater than three consecutive days in length. Data gap filling should use documented mathematically and scientifically sound algorithms and procedures and an audit trail should be used to track all gap-fills in observed data. Data gaps of less than 3 hours can be inferred using interpolation and curve-fitting techniques. Data gaps of longer than 3 hours should use external data sources such as data from a nearby station. All data derived through gap-filling procedures should be marked as inferred. Individual hourly heights, high and low waters, and daily means derived from inferred data should also be designated as inferred.

2.2.6.4 Computation of Monthly Means

When tabulation of the tides covers monthly time periods, monthly means of the various tidal parameters are computed for subsequent use in tidal datum determination and for quality control of long term data sets. Monthly mean sea level, for instance, is an important parameter for understanding long term sea level trends and seasonal variations in water levels. For purposes of monthly mean computation, monthly means should not be computed if gaps in data are greater than three consecutive days.

Fig. 5.15 "Example of a Monthly Tabulation of the Tide"

Jan 28 2003 08:24 HIGH/LOW WATER LEVEL DATA October, 2002
National Ocean Service (NOAA)
Station: 8454049 T.M.: 0 W
Name: QUONSET POINT, RI Units: Meters
Type: Mixed Datum: Station Datum
Note: > Higher-High/Lower-Low [] Inferred Tide Quality: Verified

High			Low		High			Low	
Day	Time	Height	Time	Height	Day	Time	Height	Time	Height
1	7.5 <20.2	8.037 8.071	2.4 <12.9	7.326 7.197	16	<9.7 <21.3	[8.292] 8.782	2.6 14.6	7.394 7.563
2	8.8 <21.4	8.000 8.176	2.6 <14.3	7.173 7.066	17	10.6 <22.8	8.345 8.323	<6.0 <15.4	7.470 7.245
3	9.5 <22.3	8.233 8.314	3.2 <15.6	7.157 7.049	18	10.7 23.3	8.257 8.230	4.0 16.7	7.248 7.196
4	10.5 <23.1	8.525 8.599	4.1 <16.3	7.163 7.057	19	<11.8 <23.4	8.296 8.292	<4.3 17.1	7.140 7.204
5	<11.5 23.8	8.632 8.466	4.4 <17.1	7.109 6.873	20	 12.4	 8.209	<5.0 <17.5	7.066 6.994
6	 12.2	 8.477	<5.8 18.2	6.670 6.832	21	0.4 <12.8	[8.128] 8.297	5.8 18.1	7.036 7.090
7	<0.5 <13.3	8.582 8.819	<6.4 19.2	6.961 6.969	22	0.9 <13.4	8.142 8.216	<6.5 19.0	6.999 7.040
8	1.3 <14.0	8.457 8.644	6.9 <20.1	6.888 6.877	23	1.4 <13.7	[8.075] [8.180]	<6.9 <19.1	7.013 6.915
9	2.3 <14.9	8.355 8.631	<7.9 20.9	6.852 6.986	24	2.1 <14.7	7.934 8.164	7.3 19.9	6.969 7.093
10	3.4 <15.8	8.316 8.497	<8.2 21.2	6.969 7.086	25	2.9 <15.4	[7.993] 8.156	<8.0 <20.3	7.047 7.136
11	4.3 <16.7	8.240 8.455	<9.4 22.1	7.129 7.305	26	3.8 <16.2	[8.061] 8.607	8.3 23.5	7.204 7.389
12	5.2 <17.7	8.295 8.462	<10.3	7.380	27	4.6 <17.1	7.974 8.216	<9.1 21.9	7.090 7.348
13	5.9 <18.7	8.266 8.344	0.5 11.8	7.481 7.461	28	5.4 <17.9	7.860 8.008	<10.5	7.064
14	6.8 <20.1	8.077 8.161	<2.2 <12.7	7.401 7.190	29	6.2 <18.6	7.949 8.042	1.5 <11.6	7.243 7.109
15	8.3 20.9	8.156 8.273	2.0 <14.1	7.349 7.344	30	7.3 <20.0	[8.052] [8.154]	<1.5 13.0	7.197 7.211
					31	8.3 <20.7	8.215 8.290	2.1 <14.1	7.239 7.222

Highest Tide: 8.819 13.3 Hrs Oct 7 2002
Lowest Tide: 6.670 5.8 Hrs Oct 6 2002

Monthly Means:	MHHW	8.357				
	MHW	8.272	DHQ	0.085		
	MTL	7.707	GT	1.266	HWI	0.42 Hrs
	DTL	7.724	MN	1.131	LWI	6.13 Hrs
	MSL	7.668				
	MLW	7.141	DLQ	0.050		
	MLLW	7.091				

2.2.7 Computation of Tidal Datums

A vertical datum is called a tidal datum when it is defined by a certain phase of the tide. Tidal datums are local datums and should not be extended into areas which have differing hydrographic characteristics without substantiating measurements. In order that they may be recovered when needed, such datums are referenced to fixed points known as bench marks.

Basic Procedures:

a. Make Observations – Tidal datums are computed from continuous observations of the water level over specified lengths of time. Observations are made at specific locations called tide stations. Each tide station consists of a water level gauge or sensor(s), a data collection platform or data logger and data transmission system and a set of tidal bench marks established in the vicinity of the tide station. The US National Ocean Service (NOS) collects water level data at 6 minute intervals.

b. Tabulate the Tide – Once water level observations are quality controlled and any small gaps filled, the data are processed by tabulating the high and low tides and hourly heights for each day. Tidal parameters from these daily tabulations of the tide are then reduced to mean values, typically on a calendar month basis for longer period records or over a few days or weeks for shorter-term records.

c. Compute Tidal Datums – First reduction tidal datums are determined directly by meaning values of the tidal parameters over a 19 year NTDE (National Tidal Datum Epoch). Equivalent NTDE tidal datums are computed from tide stations operating for shorter time periods through comparison of simultaneous data between the short term station and a long term station.

d. Compute Bench Mark Elevations – Once the tidal datums are computed from the tabulations, the elevations are transferred to the bench marks established on the land through the elevation differences established by differential levelling between the tide gauge sensor 'zero' and the bench marks during the station operation. The bench mark elevations and descriptions are disseminated by NOS through a published bench mark sheet for each station. Connections between tidal datum elevations and geodetic elevations are obtained after levelling between tidal bench marks and geodetic network benchmarks. Traditionally, this has been accomplished using differential levelling, however GPS surveying techniques can also be used (NGS, 1997).

The locations of tide stations are organized into a hierarchy:

a. Control tide stations are generally those which have been operated for 19 or more years, are expected to continuously operate in the future and are used to obtain a continuous record of the water levels in a locality. Control tide stations are sited to provide datum control for national applications and located in as many places as needed for datum control.

b. Secondary water level stations are those which are operated for less than 19 years but more than 1 year and have a planned finite lifetime. Secondary stations provide control in bays and estuaries where localized tidal effects are not realized at the nearest control station. Observations at a secondary station are not usually sufficient for a precise independent determination of tidal datums, but when reduced by comparison with simultaneous observations at a suitable control tide station very satisfactory results may be obtained.

c. Tertiary water level stations are those which are operated for more than a month but less than 1 year. Short-term water level measurement stations (secondary and tertiary) may have their data reduced to equivalent 19 year tidal datums through mathematical simultaneous comparison with a nearby control station.

Control (or primary) tide stations, secondary stations and tertiary stations are located at strategic locations for network coverage. The site selection criteria include spatial coverage of significant changes in tidal characteristics such as: changes in tide type, changes in range of tide, changes in time of tide, changes in daily mean sea level and changes in long term mean sea level trends. Other criteria include coverage of critical navigation areas and transitional zones, historical sites, proximity to the geodetic network and the availability of existing structures, such as piers suitable for the location of the scientific equipment.

Procedure for Simultaneous Comparison:

Conceptually, the following steps need to be completed in order to compute equivalent NTDE tidal datums at short term stations using the method of comparison of simultaneous observations:

a. select the time period over which the simultaneous comparison will be made;

b. select the appropriate control tide station for the subordinate station of interest;

c. obtain the simultaneous data from subordinate and control stations and obtain or tabulate the tides and compute monthly means, as appropriate;

d. obtain the accepted (relative to the NTDE in the U.S. for example) values of the tidal datums at the control station;

e. compute the mean differences and/or ratios (as appropriate) in the tidal parameters between the subordinate and control station over the period of simultaneous comparison;

f. apply the mean differences and ratios computed in step e, above, to the accepted values at the control station to obtain equivalent or corrected NTDE values for the subordinate station.

Compute Bench Mark Elevations.

Once the tidal datums are computed from the tabulations, the elevations are transferred to the bench marks established on the land through the elevation differences established by differential levelling between the tide gauge sensor ‘zero’ and the bench marks during the station operation (NOS Specifications and Deliverables, 2000). Connections between tidal datum elevations and geodetic elevations are obtained after levelling between tidal bench marks and geodetic network benchmarks. Traditionally, this has been accomplished using differential levelling, however GPS surveying techniques can also be used (NGS, 1997).

2.2.7.1 Tidal Datum Recovery

Whenever tide stations are installed at historical sites, measures should be taken to ‘recover’ the established tidal datums through levelling which should be accomplished by referencing the gauge or tide staff ‘zero’ to more than one existing bench mark with a published tidal elevation. Through this process, the published MLLW elevation is transferred by level differences to the ‘new’ gauge or tide staff and compared to the MLLW elevation computed from the new data on the same ‘zero’. Factors affecting the datum recovery (i.e. differences between old and newly computed datums) include the length of each data series used to compute the datums, the geographical location, the tidal characteristics in the region, the length of time between re-occupations, the sea level trends in the region and the control station used. Based on all of these factors, the datum recovery can be expected to vary from +/- 0.03 m to +/- 0.08 m. Hence, this process also serves as a very useful quality control procedure. After a successful datum recovery is performed and benchmark stability is established, the historical value of Mean Lower Low Water (MLLW) should be used as the operational datum reference for data from the gauge during hydrographic survey operations.

2.2.7.2 Quality Control of Datums

It is essential for tidal datum quality control to have data processing and levelling procedures carried out to the fullest extent. Caution must also be used in computing tidal datums in riverine systems or in regions of unknown tidal regimes. Tide-by-tide comparisons between subordinate and control station data will often detect anomalous differences which should be investigated for possible gauge malfunction or sensor movement. Datums should be established from more than one bench mark. Differences in elevations between bench marks based on new levelling must agree with previously established differences from the published bench mark sheets. Any changes in the elevation differences must be reconciled before using in any datum recovery procedure. Datum accuracy at a subordinate station depends on various factors, but availability and choice of an adequate control station of similar tidal characteristics, similar daily mean sea level and seasonal mean sea level variations, and similar sea level trends are the most important. The length of series will also determine accuracy. The longer the series, the more accurate the datum and the greater quality control and confidence gained from analyzing numerous monthly mean differences between the subordinate and control station. At re-occupied historical stations for which datum recoveries are made, updated datums should be computed from the new time series and compared with the historical datums as the survey progresses.

2.2.7.3 Geodetic Datum Relationships

Tidal datums are local vertical datums which may change considerably within a geographical area. A geodetic datum is a fixed plane of reference for vertical control of land elevations. The North American Vertical Datum of 1988 (NAVD 88) is the accepted geodetic reference datum of the U.S. National Geodetic Spatial Reference System and is officially supported by the National Geodetic Survey (NGS) through a network of GPS continuously operating reference stations. The relationship of tidal datums to NAVD has many hydrographic, coastal mapping and engineering applications including monitoring sea level change and the deployment of GPS electronic chart display and information systems, etc. In some countries, the local datum of Mean Sea Level (MSL) has been confused over time with the national geodetic reference datum because the geodetic datums were originally derived from MSL measurements at tide gauges. However as relative sea level has changed with vertical land movement and global sea level rise, the geodetic datums became de-coupled from local oceanographic MSL. NAVD88, for instance, used only one tide station as a starting reference and is not considered a MSL correlated datum.

Existing geodetic marks in the vicinity of a subordinate tidal station should be searched for and recovered. A search routine is available at **http://www.ngs.noaa.gov**. An orthometric level connection and ellipsoidal GPS tie is required at a subordinate tide station which has geodetic bench marks located nearby. NAVD 88 height elevations for published bench marks are given in Helmert orthometric height units by NGS. The GPS ellipsoid network height accuracies are classified as conforming to 2 cm or 5 cm standards accuracies (Refer to NOAA Technical Memorandum NOS NGS-58). At the present time, GPS ellipsoid heights conforming to the 2 cm accuracy standards are required for contract hydrographic surveying projects. Refer to Section 4.2.8 GPS Observations and User's Guide for GPS Observations, NOAA/NOS, updated January 2003.

An orthometric level connection is preferred over ellipsoidal GPS tie, where applicable, for deriving NAVD 88 heights. An orthometric level connection is required if any geodetic marks (up to five marks) are located within a radius of 0.8 km from the subordinate tide station location. If suitable marks are found in the NGS database, and are farther than 0.8 km but less than 10 km from a subordinate tide station, then a GPS tie is required to derive the ellipsoid heights. If a minimum of five existing tidal bench marks within 1 km of a subordinate tide station location are not found, or suitable geodetic marks are not found in the NGS database within 10 km of a subordinate tide station, then five new bench marks should be installed, described, connected by levels, and GPS observations should be undertaken on at least one of the five marks. (Refer to User's Guide for Writing Bench Mark Descriptions, NOAA/NOS, Updated January 2002, User's Guide for GPS Observations, NOAA/NOS, Updated January 2003, and Section 4.2.8 GPS Observations.) At least two geodetic bench marks should be used to validate the levelling or GPS ellipsoid height connection for quality control purposes.

2.2.8 Final Zoning and Tide Reducers

Data relative to MLLW from subordinate stations installed specifically for the survey, or from existing primary control stations, as appropriate, should be applied to reduce sounding data to chart datum, either directly or indirectly through a correction technique referred to as tidal zoning. Whether corrected or direct, time series data relative to MLLW or other applicable LWD applied to reference hydrographic soundings to chart datum are referred to as 'tide reducers' or 'water level reducers'.

2.2.8.1 Construction of Final Tidal Zoning Schemes

As tidal characteristics vary spatially, data from deployed water level gauges may not be representative of water levels across a survey area. Tidal zoning should be implemented to facilitate the provision of time series water level data relative to chart datum for any point within the survey area such that prescribed accuracy requirements are maintained for the water level measurement component of the hydrographic survey. NOS currently utilises the 'discrete tidal zoning' method for operations, where survey areas are broken up into a scheme of cells bounding areas of common tidal characteristics. The minimum requirement is for a new cell for every 0.06 m change in mean range of tide and every 0.3 hour progression in time of tide (Greenwich high and low water intervals). Phase and amplitude corrections for appropriate tide station data should be assigned to each cell.

Preliminary zoning, which is based on available historical tide station data and estuarine and global tide models, is referenced to an applicable predictions reference station for utilisation during field work. For final processing, preliminary zoning should be superseded by 'final zoning' which is a refinement based on new data collected at subordinate stations during the survey. With the final zoning scheme, correctors for each zone should be derived from a subordinate station specifically installed for the survey rather than the reference station used with preliminary zoning. Zoning errors should be minimized such that when combined with errors from actual water level measurement at the gauge and errors in reduction to chart datum, the total error of the tide reducers is within specified tolerances. The final zoning scheme and all data utilized in its development should be documented and submitted.

2.2.8.2 Tide Reducer Files and Final Tide Note

Verified time series data collected at appropriate subordinate stations are referenced to the NTDE Mean Lower Low Water (Chart Datum) through datum computation procedures. Time series data collected in six minute intervals and reduced to chart datum as specified, both from subordinate gauges operated during the survey should be used either directly or corrected through use of a zoning scheme such that tide reducers are within specified tolerances. A Final Tide Note should be submitted for each hydrographic sheet with information as to what final tidal zoning should be applied to which stations to obtain the final tide reducers. An example Final tide Note and final tidal zoning graphic is found in Figures 5.16 and 5.17.

Fig. 5.16 “FINAL TIDE NOTE and FINAL TIDAL ZONING CHART”

DATE: December 22, 1999

HYDROGRAPHIC BRANCH: Pacific
HYDROGRAPHIC PROJECT: OPR-P342-RA-99
HYDROGRAPHIC SHEET: H-10910

LOCALITY: 6 NM Northwest of Cape Kasilof, AK

TIME PERIOD: July 22 - August 20, 1999

TIDE STATION USED: 945-5711 Cape Kasilof, AK
Lat. 60° 20.2'N Lon. 151° 22.8'W
PLANE OF REFERENCE (MEAN LOWER LOW WATER): 0.000 meters
HEIGHT OF HIGH WATER ABOVE PLANE OF REFERENCE: 5.850 meters

REMARKS: RECOMMENDED ZONING
Use zone(s) identified as: CK394, CK395, CK399, CK400, CK401, CK407, CK408, CK409, CK434, CK435, CK441, CK442, CK443, CK467, CK468, CK469, CK470, CK477, CK480, CK481, CK482, CK483, CK493 & CK494.

Refer to attachments for zoning information.

Note 1: Provided time series data are tabulated in metric units (Meters), relative to MLLW and on Greenwich Mean Time.

Note 2: Nikiski, AK served as datum control for subordinate tide stations and for tidal zoning in this hydrographic survey. Accepted datums for this station have been updated recently and have changed significantly from previous values.

The current National Tidal Datum Epoch (NTDE) used to compute tidal datums at tide stations is the 1960-78 NTDE. Traditionally, NTDEs have been adjusted when significant changes in mean sea level (MSL) trends were found through analyses amongst the National Water Level Observation Network (NWLON) stations. Epochs are updated to ensure that tidal datums are the most accurate and practical for navigation, surveying and engineering applications and reflect the existing local sea level conditions. For instance, analyses of sea level trends show that a new NTDE is necessary and efforts are underway to update the 1960-1978 NTDE to a more recent 19 year time period.

Note: This example of Field Tide Note and Final Tidal Zoning Chart was written in December 1999, at that time NTDE was 1960-1978, now the new NTDE is 1983-2001.

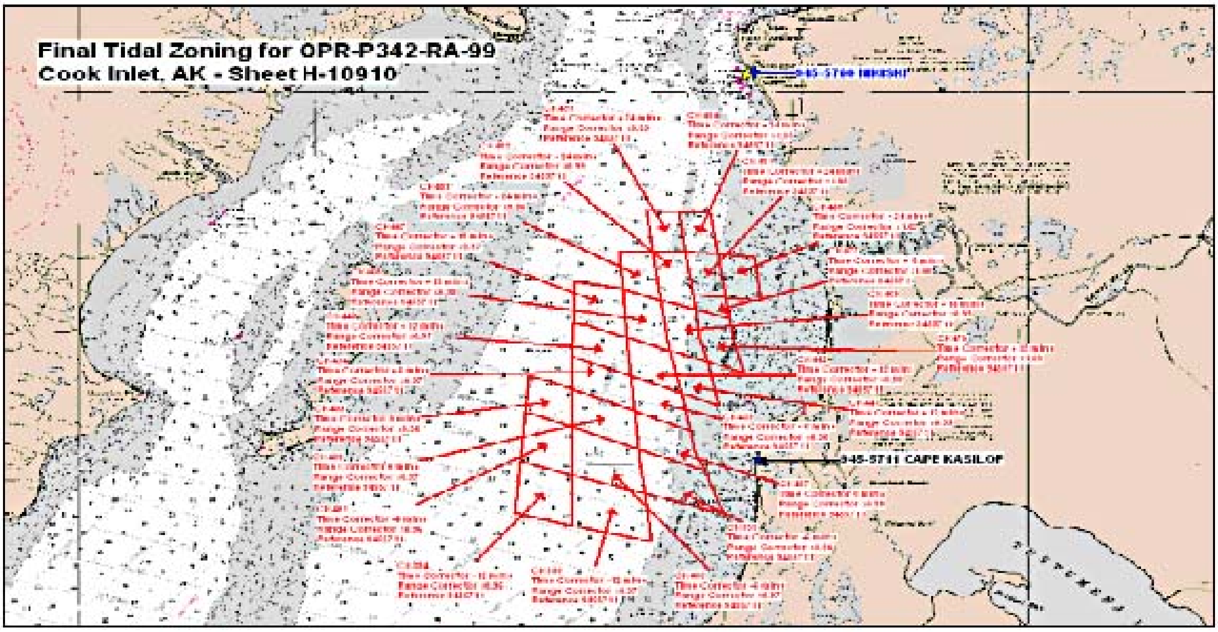


Fig. 5.17

The final observed water level measurements should be reported as heights in meters to three decimal places (i.e. 0.001 m). All heights should be referenced to station datum and should be referenced to UTC. The final tide reducer time series data should be referenced to MLLW and should be referenced to UTC.

The original raw water level data and also the correctors used to convert the data to chart datum should be retained until notified in writing or at least two years after the survey is completed. All algorithms and conversions used to provide correctors should be fully supported by the calibrations, maintenance documentation, levelling records and sound engineering/oceanographic practices. Sensors for measurements used to convert data (i.e. pressure to heights) should be calibrated and maintained for the entire water level collection period.

2.2.9 Using Kinematic GPS for Vertical Control

The technology of using Kinematic GPS for vertical control in hydrographic surveying is becoming much more commonplace after being in a research-to-operations mode for several years. Kinematic GPS is a form of centimetre level-differential positioning which uses primarily carrier phase observables in which the differential corrections are formulated in conjunction with a mobile GPS receiver (i.e. a ship or launch) and at least one static base station.

Kinematic GPS requires an accurate horizontal and vertical reference frame in order to determine an accurate position on each sounding, relative to NAD83 (for instance), and to determine an accurate depth of each sounding such as MLLW, LAT or other appropriate local chart datum. The issue of determining the separation between kinematic differential GPS vertical datum and the local chart datum is important to resolve for each survey area. This separation is not constant and may be quite complex. They are usually not well known and may require additional measurements to understand the complexity of the geodesy in the area as well as the tidal characteristics. Constant relationships may be adequate in small survey areas, simple interpolation in others; or complex interpolation models and continuous zoning schemes may be required. Tidal datums, bathymetry and geodesy must be put into the same vertical reference frame prior to the survey operations.

The availability of control for use of kinematic GPS for surveying must be evaluated during planning and if required, geodetic and tidal datum control must be established before operational collection of soundings to establish the relationship of the tidal datum and GPS reference surfaces throughout the survey area. The amount of field work required is dependent on the adequacy of existing tide and geodetic control (NOS, 2000).

3. WATER LEVEL FLOW AND TIDAL CURRENTS

3.1 Introduction

The hydrographer is required to have working knowledge of predicted and observed oceanographic and meteorological conditions to be able to conduct successful field data collection surveys and to conduct safe and efficient navigation necessary for the surveys. Besides the rise and fall of the tides, the tidal currents are often a predominant variable that affects field operations. Often the hydrographer is not only required to take soundings for nautical chart production, but must assess the tidal characteristics and the movements of the tidal currents and be able to describe them for such applications as the coast pilot volumes and tidal prediction products. In addition, the hydrographer is often required to deploy and retrieve current meter instrumentation and moorings.

3.2 Principles of Tidal Currents

Water current is horizontal movement of water. Currents may be classified as tidal and non-tidal. Tidal currents are caused by gravitational interactions between the Sun, Moon, and Earth and are part of the same general movement of the oceans which results in the vertical rise and fall of the tide. Non-tidal currents include the permanent currents in the general circulatory systems of the sea as well as temporary currents arising from more pronounced meteorological variability.

Much like tidal datums and heights, various countries use various terminology to describe the same phenomena. The United Kingdom uses the term tidal streams instead of tidal current and the term tidal flow to describe the actual flow or total current flow, which is a combination of tidal and non-tidal components.

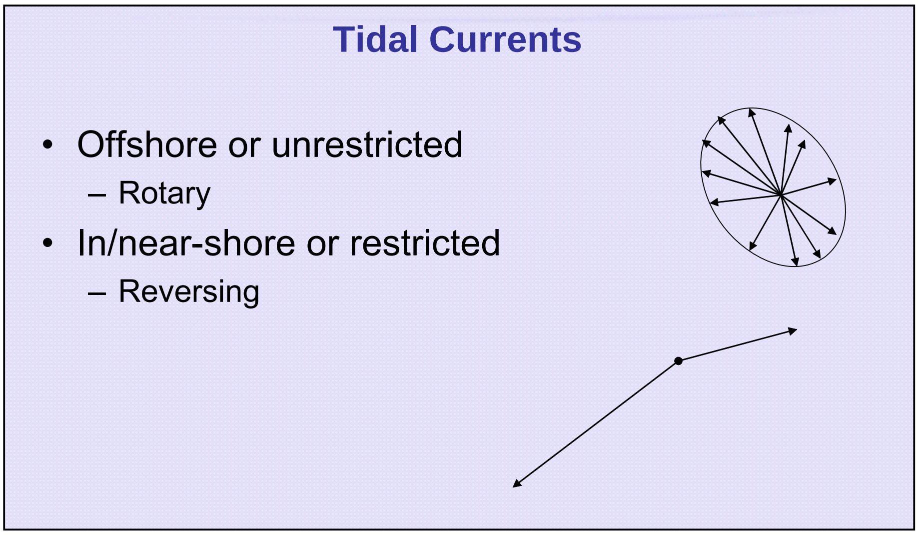
Residuals are sometimes referred to as the difference between observed total and predicted tidal currents or the difference between tidal streams and tidal flow. Although tidal currents are derived from the same tide producing forces as the tide, tidal currents are much more variable and complex to predict than the tidal heights. The rise and fall of the tide is termed a scalar (varying heights only) quantity while tidal currents are vector (both speed and associated direction vary) quantities. Speed and direction of currents at a given location not only vary over time, but with depth as well. And the characteristics of the current at any given location cannot be extended very far, especially in areas of complex shallow water bathymetry and complex topography (shoreline configurations). Current patterns in complex areas also may exhibit eddies and gyres of various sizes set up by bathymetry and channel configuration on shallow waters. It is not uncommon to find current shear patterns in which there are significant changes in direction and amplitude. Because of this spatial variability, tidal predictions derived from a current meter measurement are typically only valid for a small area at a given depth, and are not necessarily transferable within a region or throughout a water column.

Types of non-tidal currents include:

- Oceanic circulation currents;
- Gyres, Western and Eastern Boundary currents, Equatorial counter-current, etc.;
- Thermohaline circulation;

- Wind driven currents (Ekman to about 100M);
- Seiches;
- River flow and hydraulic currents.

In the open ocean, tidal currents or streams tend to be rotary in nature (Figure 5.18). In theory if the earth were covered completely by water, at the time when the earth or sun is aligned with the Equator, the tidal currents at the equator would move back and forth (east and west) in a reversing manner in response to the tides. With latitude, the currents would show elliptical patterns increasing with latitude to a circular pattern at the poles. The pattern at any given latitude would vary depending upon declination of the Moon or Sun. The effects of coriolis force also reinforce the rotary nature of the currents on the ocean such that they rotate clockwise in the northern hemisphere and counter(anti)-clockwise in the southern hemisphere.



Tidal Currents

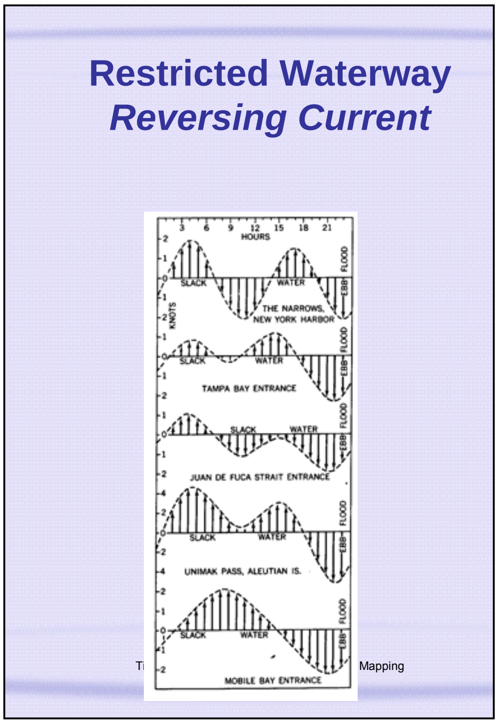
- Offshore or unrestricted
  - Rotary
- In/near-shore or restricted
  - Reversing

Fig. 5.18

In the near shore areas, tidal currents and streams tend to be more reversing in nature responding to the bathymetry and topography of the estuaries and bays (Figure 5.19). The phases of reversing currents are described as having slack periods, maximum floods and maximum ebbs. Slack water is the short time period between the reversal from flood to ebb. Typically, flood currents are those which are incoming or towards the shore or upstream. Ebb currents are those which are outgoing, offshore or downstream. These tides will show many of the characteristics of the tide described for tidal heights. Floods and ebbs will display semi-diurnal, mixed and diurnal tide characteristics very similar to the corresponding tidal height characteristics in a given area. Their strengths and velocities will exhibit variations in response to changing declinations of the Moon and Sun and to the perigee/apogee and perihelion/aphelion cycles (Figure 5.4). Tidal currents in mixed tide regimes display inequalities in the floods and ebbs each day, just like the tidal heights.

The current direction is sometimes referred to as the set and the speed is sometimes referred to as the drift. The current direction, by convention, is the compass direction toward which current flows (the opposite of the convention for winds). Speeds are defined in terms of knots (navigation) or meters/sec (scientific) (1 knot = 0.51444 m/s).

Hydraulic currents are currents due to the height difference in water level of two interconnected basins (Hell's Gate New York, Cape Cod Canal & the Chesapeake and Delaware Canal). The height differences in tidal waters are caused by the phase difference in the tide at each end of a strait or a canal. Non-tidal hydraulic currents occur in the interconnecting water ways of the Great Lakes for instance and typically are in a downstream direction only.



Restricted Waterway
Reversing Current

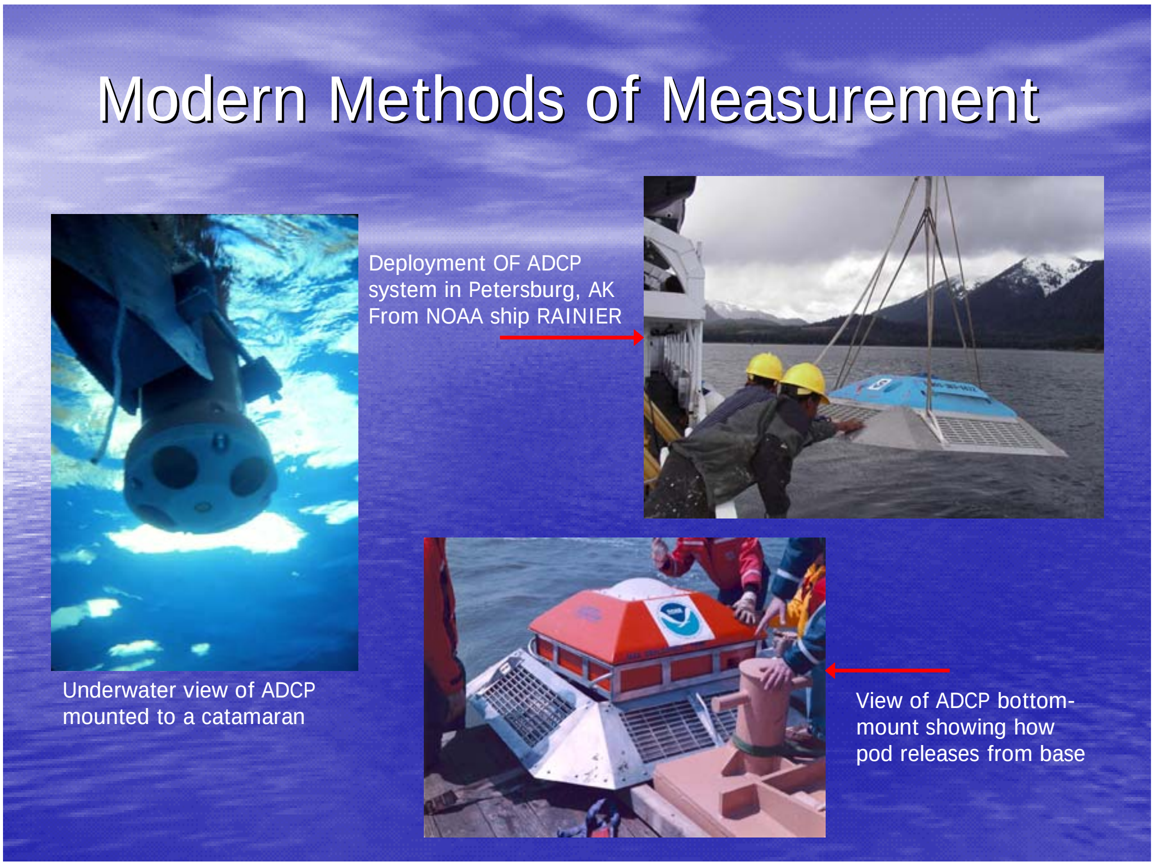
Fig. 5.19

In theory, tidal currents should have consistent relationships between the times and strengths of the flood and ebbs and the times and heights of the high and low tides because they are related and forced by the same tide producing forces. However the response of basins and estuaries to the tide producing forces and the resulting relationships of tidal current to tidal heights is complex and varies by location. In some locations, maximum currents occur at mid-tide and at others, maximum currents occur nearer high and low tides.

3.3 Measurement of Currents

There are two distinct methods for measuring currents: Lagrangian use of floats, dyes, drift cards, drifters, or current drogues and Eulerian use of a current meter at a single location(s). Both types have their advantages and disadvantages depending upon the application. Lagrangian devices require tracking of concentrations or changes in position of drifters over time, they are useful for trajectory modelling and forecasting for application to HAZMAT spills and oil spills or for studies of estuarine circulation patterns. Sub-surface drifters can also be deployed to track bottom currents. Eulerian devices provide good time series information of currents at specific locations and depths used in traditional tidal current prediction applications for recreational and commercial navigation and fisheries vessel operations. Both types of measurements are useful for complete understanding of current regimes and for the development and calibration of hydrodynamic circulation models. Hydrographic survey vessels may be required to deploy a variety of current measurement devices depending upon the survey area and the information required.

The earliest current measurement systems were Lagrangian in nature, using drifting ship tracks or using drift poles deployed from ships. For near-shore work, these were replaced by moored current meter systems of various mechanical and electro-mechanical designs. These systems are installed in sub-surface mooring designs with several meters deployed along the vertical mooring line depending upon depth with the top current meter deployed as close to the surface as possible. Mechanical current meters use combinations of vanes, rotors and propellers to measure speed and direction. The meters are generally internal recording with the data collected upon retrieval. Deployment periods are generally short-term (a few months maximum). Modern current meter systems use acoustic doppler current profiler (ADCP) technology to measure current profiles in the water column over time from a bottom mounted current meter. ADCPs can also be deployed horizontally to measure across channel currents over time at fixed depths and can be towed to measure currents with depth over cross channel transects. These current meters can also be deployed from surface buoys in a downward looking direction and can be configured to provide data in real-time using acoustic modem technology or direct cables depending upon the deployment. The ADCPs provide profiles of current speed and direction by providing information for fixed vertical bins in the water column. Figure 5.20 shows some typical deployment configurations for current meters.



Modern Methods of Measurement

Underwater view of ADCP mounted to a catamaran

Deployment OF ADCP system in Petersburg, AK From NOAA ship RAINIER

View of ADCP bottom-mount showing how pod releases from base

Fig. 5.20

New high frequency radar systems are being developed that provide surface current maps over wide-areas which should also be beneficial to conducting hydrographic survey operations. These shore-based systems use a transponder and receiver antennae to provide current vectors for fixed surface area bins in near-real-time (see Figure 5.21).

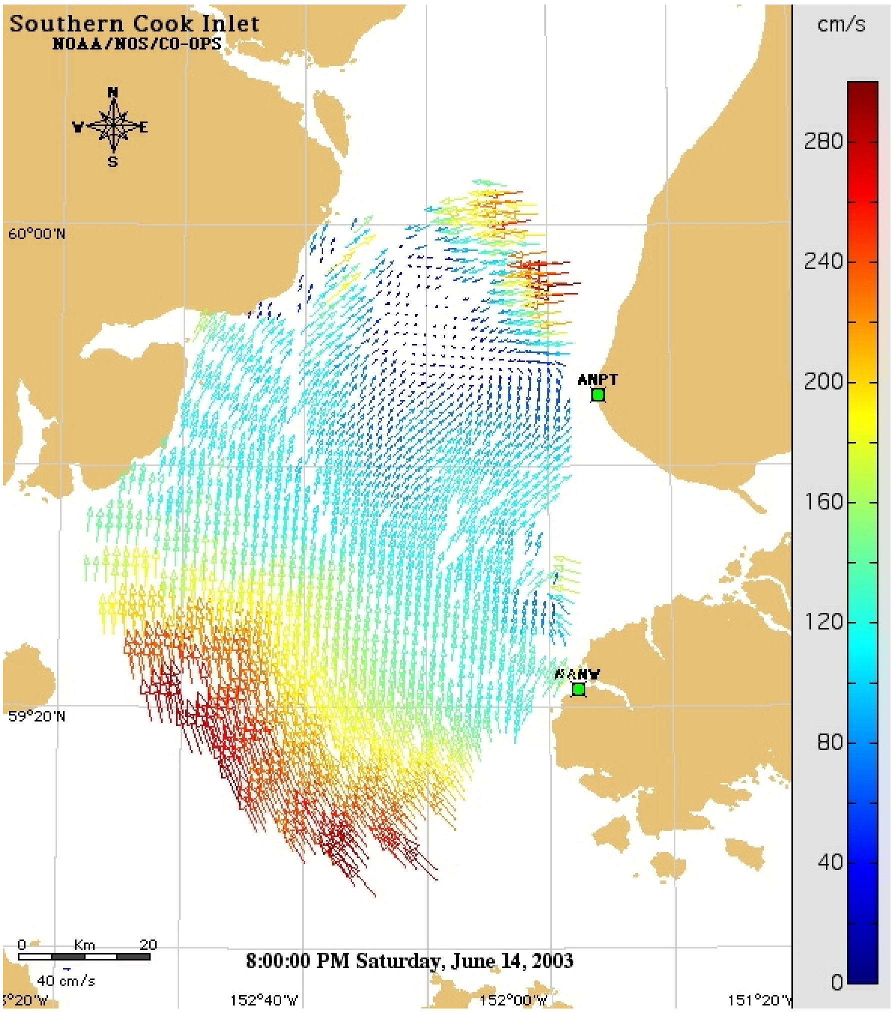


Fig. 5.21

3.4 Tidal Current Prediction

Tidal currents, like tidal heights, can be predicted because they are caused by the interaction of the well-known Earth-Moon-Sun system. Also, like tidal height predictions, tidal currents are predicted by performing harmonic analysis of measurements obtained from preferably 29 days of data to span an entire lunar month. A minimum of 15 days of data can be used for harmonic analysis currents, simply because it is historically and logistically hard to routinely obtain more than that in a typical deployment. Although the approach and theory are the same for harmonic analysis of tides and tidal currents, analyses of tidal currents are more complex. For example, for reversing currents, two sets of constituents are obtained for the major and minimum axes with the major axis being the principal current direction. In addition, the analysis must try to handle the presence of any non-tidal permanent current found in the analysis of the observations.

Mariners are generally interested in the timing and strength of four phases of the tidal current cycle. NOAA (U.S.) tide prediction tables include predictions for slack before flood (SBF), maximum flood current (MFC), slack before ebb (SBE), and maximum ebb current (MEC). In areas where the currents are never at true slack (zero speed), slack flood current (SFC) and slack ebb current (SEC) values are predicted as well. Tidal current prediction stations also utilise the same concept of reference stations and secondary stations in the tide table products such that speed ratios are used to correct daily reference station predictions to the desired location(s).

Predictions of tidal currents have similar limitations to those for tidal height predictions. Extreme care must be taken to extrapolate a tide or tidal current prediction beyond the location of the measurement. This is especially the case for tidal currents due to the nature of the spatial variation in speed and direction in shallow water estuaries and rivers, the significant affects of non-tidal forcing due to river flow, wind speed and direction and natural non-tidal circulation patterns. Just as for tidal heights, tidal current predictions are much less useful in areas with low signal-to-noise ratio (low tidal forcing relative to non-tidal forcing).

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