2. TIDAL OVERVIEW

Characteristics of the Tides

The word "tides" is a generic term used to define the alternating rise and fall of the oceans with respect to the land, produced by the gravitational attraction of the moon and sun. To a much smaller extent, tides also occur in large lakes, the atmosphere, and within the solid crust of the earth, also caused by the gravitational forces of the moon and sun. Additional non-astronomical factors such as configuration of the coastline, local depth of the water, ocean-floor topography, and other hydrographic and meteorological influences may play an important role in altering the range of tide, the times of arrival of the tides, and the time interval between high and low water. There are three basic types of tides: semidiurnal (semi-daily), mixed, and diurnal (daily).

The first type, semidiurnal (Figure 1, top), has two high waters (high tides) and two low waters (low tides) each tidal day. A tidal day is the time of rotation of the Earth with respect to the Moon, and its mean value is approximately equal to 24.84 hours. In Figure 2, semidiurnal tides are illustrated by the marigrams at Boston, New York, Hampton Roads, and Savannah. Qualitatively, the two high waters for each tidal day must be almost equal in height. The two low waters of each tidal day also must be approximately equal in height. The second type, mixed (Figure 1, middle), is similar to the semidiurnal except that the two high waters and the two low waters of each tidal day have marked differences in their heights. When there are differences in the heights of the two high waters, they are designated as higher high water and lower high water; when there are differences in the heights of the two lows, they are designated as higher low water and lower low water. In Figures 2 and 3, mixed-type tides are illustrated by the marigrams at Key West, San Francisco, Seattle, Ketchican, and Dutch Harbor. The third type, diurnal (Figure 1, bottom), has one high water and one low water each tidal day. In Figure 2, the marigram at Pensacola illustrates a diurnal tide.

The most important modulations of the tides are those associated with the phases of the moon relative to the sun (Figure 4). Spring tides are tides occurring at the time of the new and full moon. These are the tides of the greatest amplitude, meaning the highest and lowest waters are recorded at these times. Neap tides are tides occurring approximately midway between the time of new and full moon. The neap tidal range is usually 10 to 30 percent less than the mean tidal range. In addition to spring and neap tides, there are lesser, but significant monthly modulations due to the elliptical orbit of the moon about the earth (perigee and apogee) and yearly modulations due to the elliptical orbit the earth about the sun (perihelion and aphelion). Modulations in mixed and diurnal tides are especially sensitive to the monthly north and south declinations of the moon relative to the earth's equator (tropic tides and equatorial tides) and to the yearly north and south declinations of the sun(equinoxes and solstices).

There is another important longer period modulation in the amplitude of the tide due to orbital paths of the earth and moon. The apparent path of the Earth about the Sun, as seen from the Sun, is called the ecliptic. This path may be represented on a globe of the Earth by drawing a great circle about the Earth which makes an angle of $23^{o}\ 27'$ relative to the Earth's equator (Figure 5). Likewise, the apparent path of the moon about the sun may be referenced to the ecliptic, such that the moon's path about the sun makes an angle of 5^{o} with respect to the ecliptic. When the moon's ascending node corresponds to the vernal (i.e., spring) equinox (the equinoxes are the two times of the year, March 21 and September 23, when the sun crosses the earth's equator, and day and night have the same length), the angle of the path of the moon about the sun is about 28.5° (Schureman, 1941). When the moon's descending node corresponds to the vernal equinox, the angle of the moon's path about the sun is about 18.5° . This variation in the path of the moon about the sun has a period of about 18.6 years, and is called the regression of the moon's nodes. The regression of the nodes introduces an important variation into the amplitude of the annual mean range of the tide, as may be seen in Figure 6. It is the regression of the moon's nodes which forms the basis of the definition of the National Tidal Datum Epoch (NTDE) (see Chapter 6). Figure 6 also shows the monthly mean range which is due to seasonal and meteorological effects. Because the variability of the monthly mean range is larger than that due to the regression of the nodes, the NTDE is defined as an even 19-year period to obtain closure on a calendar year so as not to bias the estimate of the tidal datum.

Although the astronomical influences of the moon and sun upon the earth would seem to imply a uniformity in the tide, the type of tide can vary both with time at a single location (Figures 2 and 3) and in distance along the coast (Figure 7). The transition from one type to another is usually gradual either temporally or spatially, resulting in hybrid or transition tides. A good example in Figure 2 is Galveston which transitions from diurnal to semidiurnal to mixed. Key West (Figure 2) transitions from mixed to semidiurnal to mixed. Dutch Harbor (Figure 3) shows similar transitions. Figure 7 shows the gradual spatial transitions from mixed to diurnal to mixed and back to diurnal.

Photocopies of the NOAA pamphlet *Our Restless Tides* presents a layman's overview of tide producing forces and tidal observations and is available from CO-OPS.

DISTRIBUTION OF TIDAL PHASE

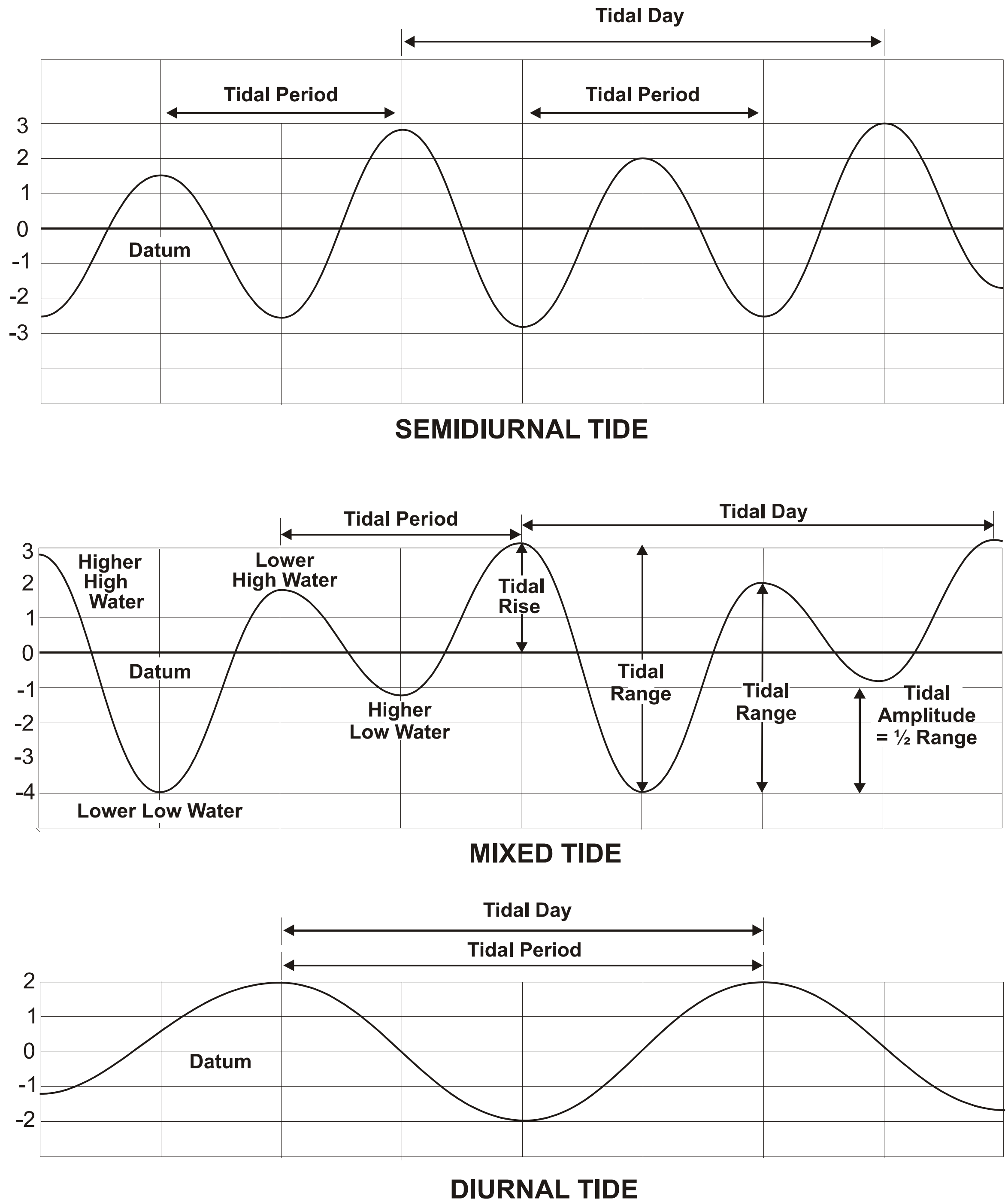
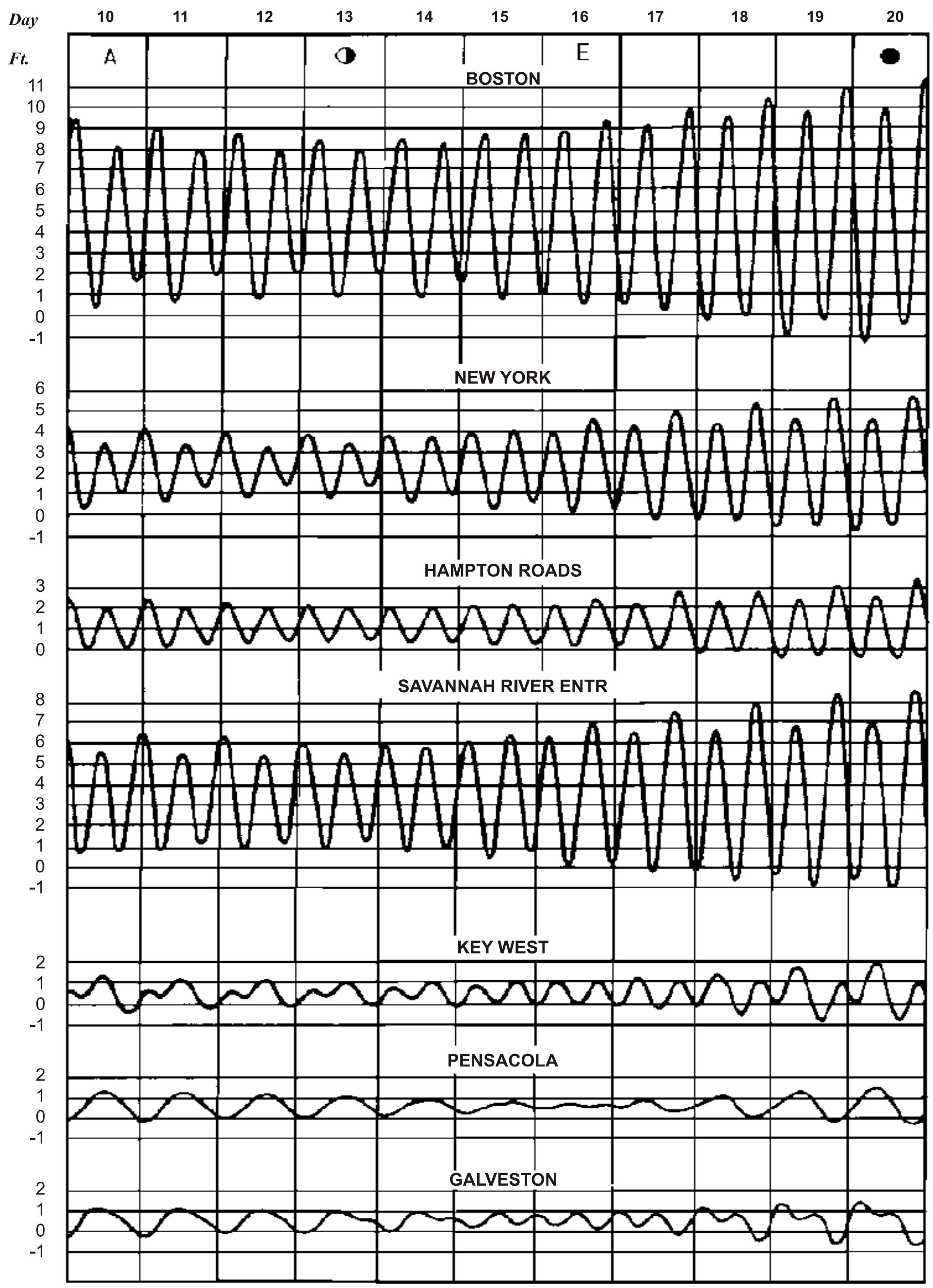


Figure 1. A depiction of the three primary kinds of tides. From the top panel downward they are semidiurnal, mixed, and diurnal. Standard tidal terminology is used to describe the various aspects of the tides. The zero on these graphs is illustrative of the relationship of the tides to Mean Sea Level (MSL).

TYPICAL TIDE CURVE FOR UNITED STATES PORTS



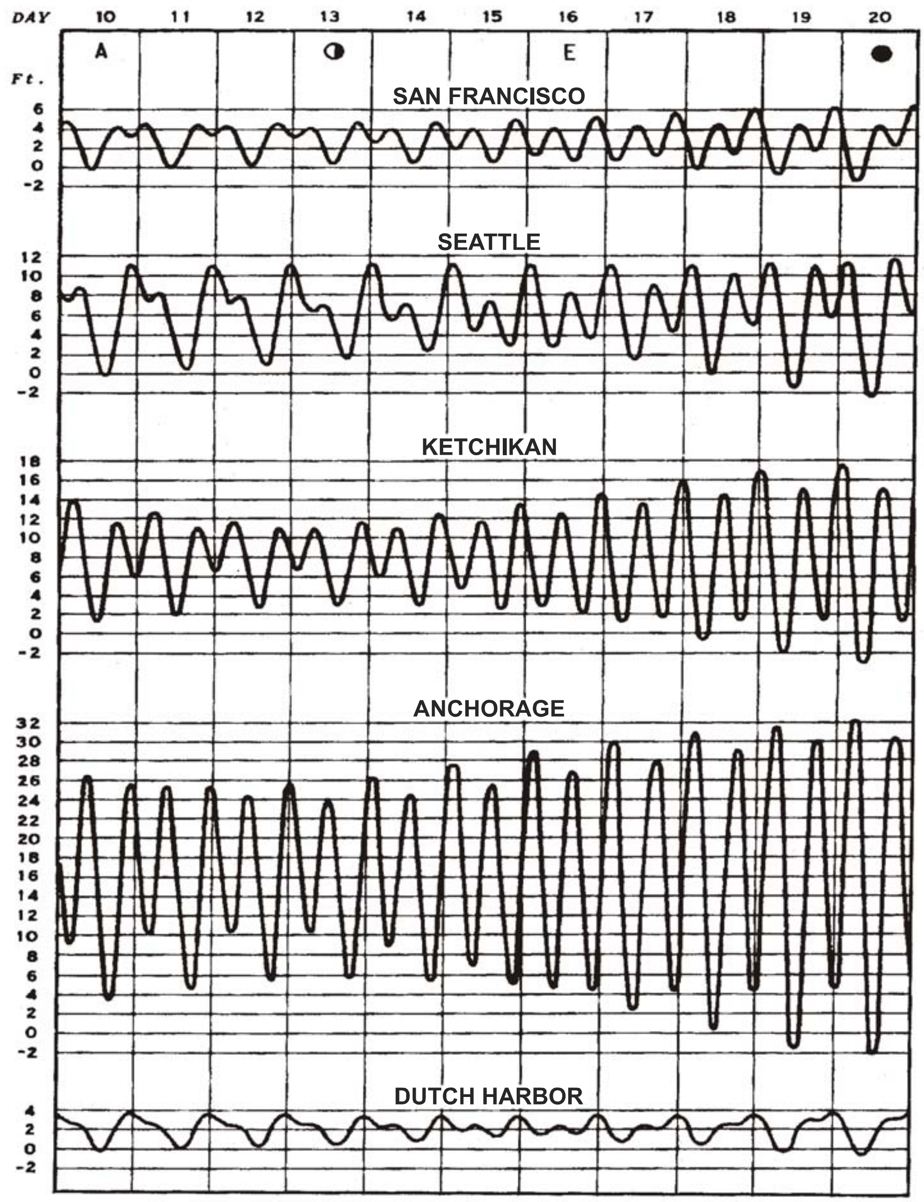
A discussion of these curves is given on the preceding page.

Lunar data:

A - Moon in apogee
◑ - last quarter
E - Moon on Equater
● - new Moon

Figure 2. Characteristic tide curves near port facilities along the U.S. East and Gulf Coasts. The tides depicted are primarily semidiurnal along the East Coast. The tides at Pensacola are primarily diurnal. The effects of the phases of the moon are also illustrated. The elevations in feet of the tide are referenced to the tidal datum mean lower low water.

TYPICAL CURVES FOR UNITED STATES PORTS



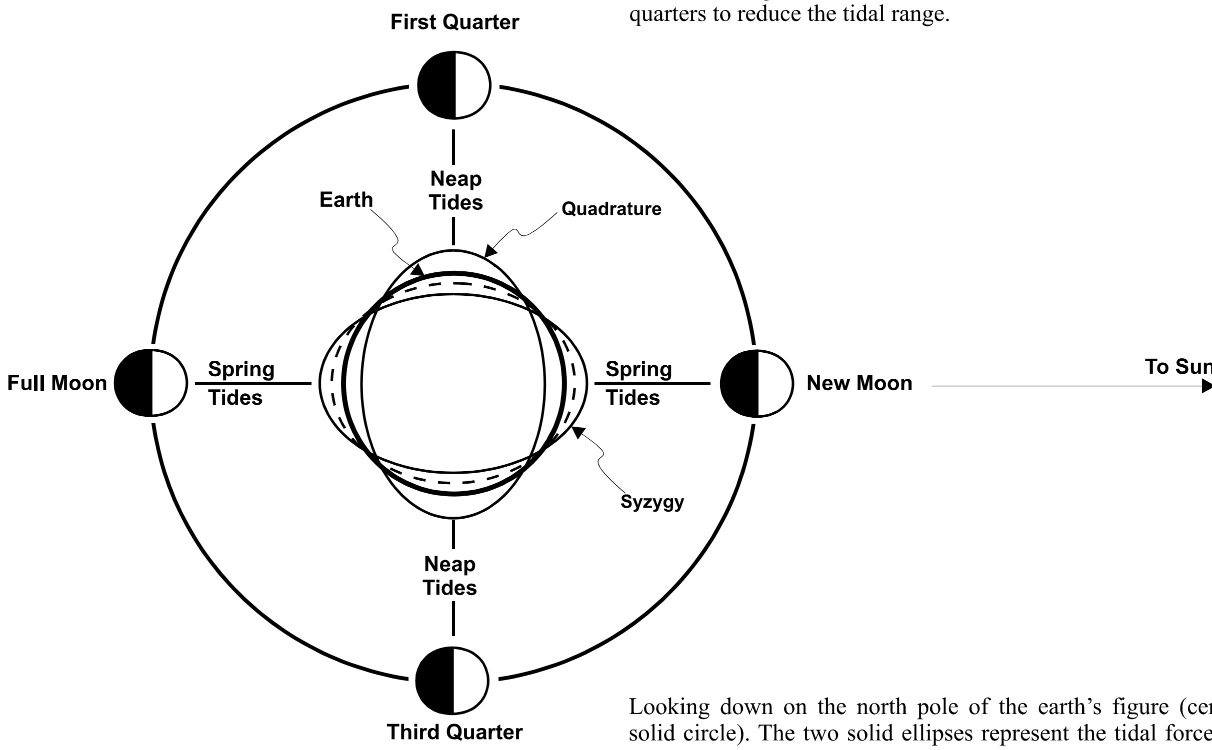
A discussion of these curves is given on the preceding page.

Lunar data:
A - Moon in apogee
◑ - last quarter
E - Moon on Equator
● - new Moon

Figure 3. Characteristic tide curves for the West Coast. The tides depicted are primarily mixed. The tidal range at Anchorage is relatively large. The effects of the phases of the moon are also illustrated. The elevations in feet of the tide are referenced to the tidal datum, mean lower low water.

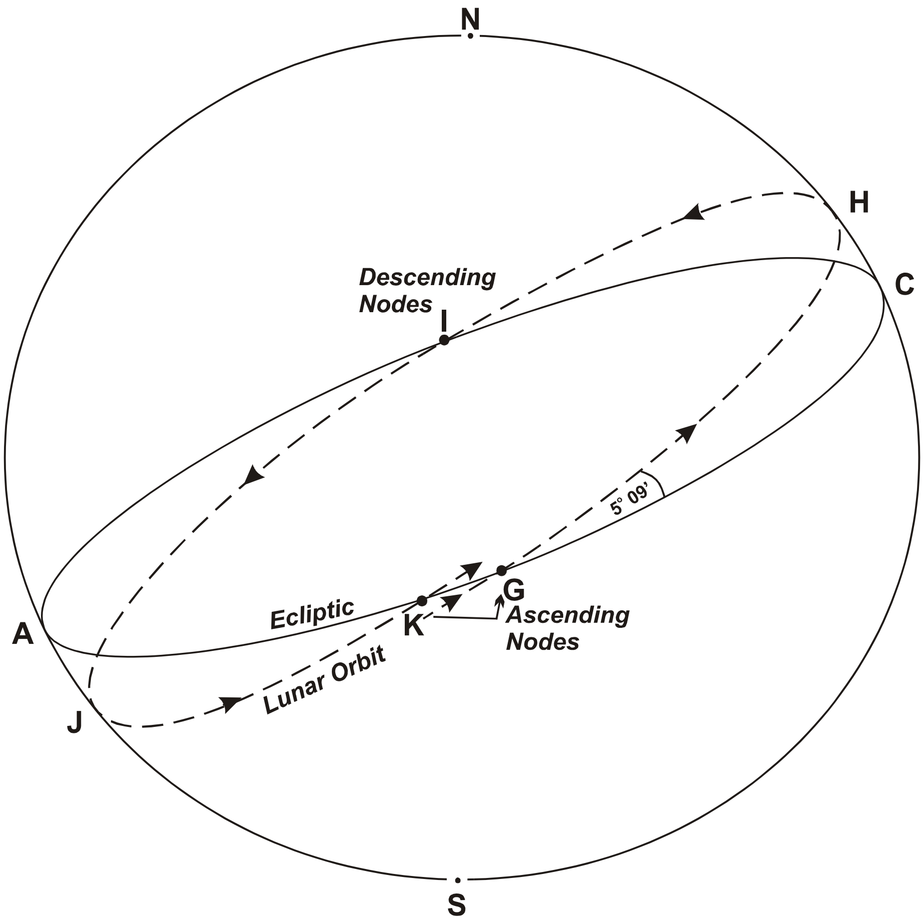
The Phase Inequality; Spring and Neap tides

The gravitational attraction (and resultant tidal force envelopes) produced by the moon and sun reinforce each other at times of new and full moon to increase the range of the tides, and counteract each other at first and third quarters to reduce the tidal range.



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 or third quarter), respectively; the dashed ellipse shows the smaller tidal force envelope produced by the sun.

Figure 4. An illustration of solar and lunar tide producing forces. The largest tides, spring tides, are produced at new and full moon. The smallest tides, neap tides, occur during the first and third quarters of the moon.



Motion of the moon's nodes. The points where the moon's path crosses the ecliptic are called nodes; the point where the moon crosses the ecliptic from south to north at *G* is called the ascending node, while *I* is called the descending node. The moon's orbit from the ascending node *G* to the next ascending node K takes *27.2122* mean solar days (the Draconitic Period). Measured relative to a fixed star the moon takes *27.3216* mean solar days to complete its orbit (the Sidereal Period). The movement of the nodes westwards along the ecliptic is called the regression of the nodes; it is analogous to the precession of the equinoxes along the equator but is much faster, having a period of *18.61* years. This is equivalent to *27.3216-27.2122=0.1094* days per orbit; in the diagram it is represented by the distance *KG*.

Figure 5. A diagram illustrating the regression of the moon's nodes.

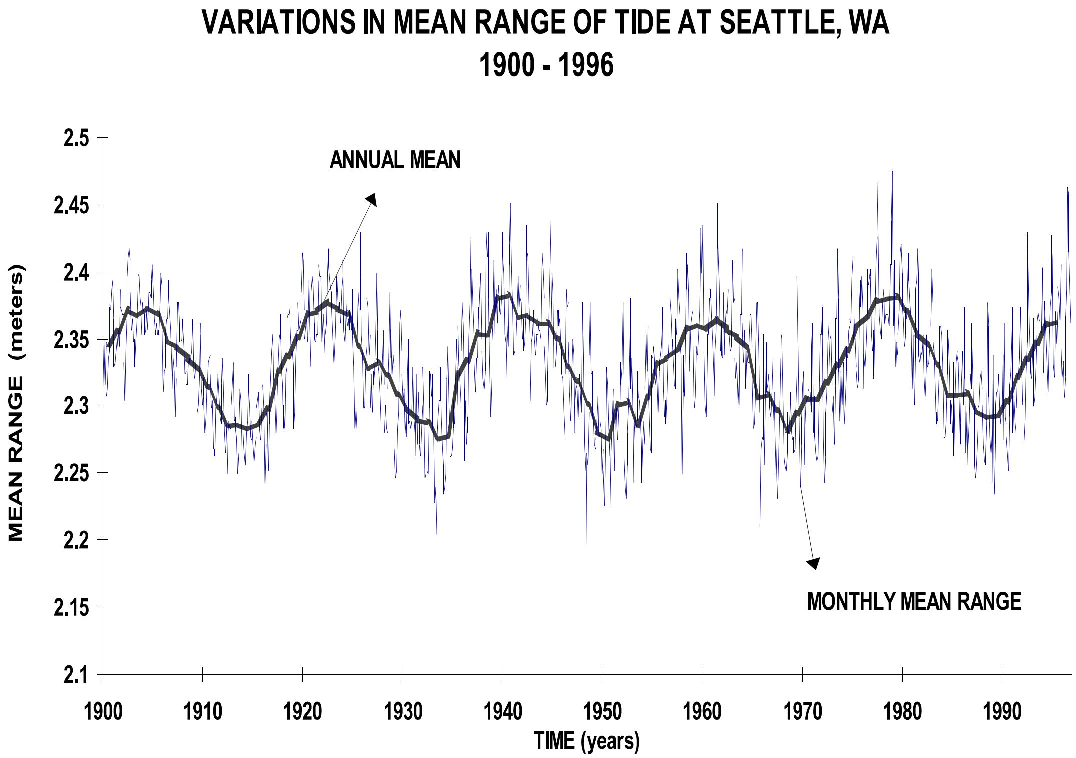


Figure 6. An illustration of the effect of the regression of the moon's nodes on the water levels at Puget Sound, WA. The heavy black curve is the annual mean range, or the difference in height between mean high water and mean low water. The time elapsed between trough to trough, or peak to peak, is the period of oscillation of the regression, and is about 18.6 years.

Tidal Analysis and Predictions

The routine prediction of tides is based upon a simple principle that for a linear system whose forcing can be decomposed into a sum of harmonic terms of known frequency (or period), the response can also be represented by a sum of harmonics having the same frequencies (or periods) but with different amplitudes and phases from the forcing. The tides are basically such a system (*e.g., Schureman, 1941*), due to their astronomical cycles imposed by the motions of the earth, sun, and moon. However, the system is not truly linear, and, in making tidal predictions, sums, differences, and harmonics of forcing frequencies are considered to approximately incorporate nonlinear effects (e.g., *Schureman, 1941*). For the open coastal regions, the tidal prediction capability requires only prior observations of the tides at the location of interest over a suitable period of time from which the amplitudes and phases of the major harmonic constituents can be ascertained by tidal analysis. For tide prediction reference stations, NOS generally uses a minimum one year of hourly water level observations to compute the semi-diurnal and diurnal tidal frequencies and a separate analysis of several years of monthly mean sea levels to compute the solar annual and solar semiannual, S_a and $S_{sa,}$ terms. Resolving S_a and S_{sa} may require on the order of 10 years of water level data (*Scherer, 1990*). Typically, NOS uses up to 37 amplitudes and phases for important periods (period= 1/frequency) required to reconstitute a tidal signal.

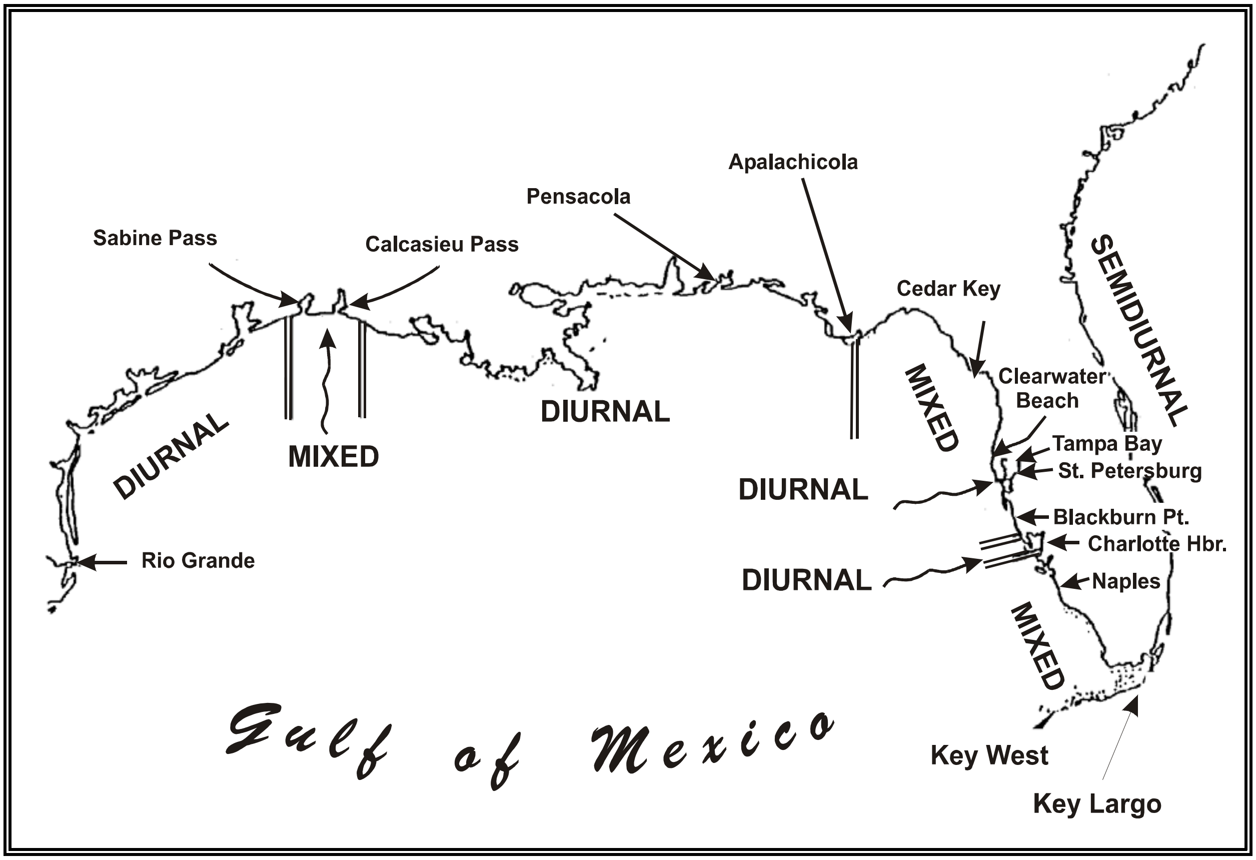


Figure 7. An illustration of the spatial variability of the type of tide in the Gulf of Mexico.

Harmonic Constituents

The component tides are usually referred to as harmonic constituents. The principal harmonic constituents of the tide (*e.g., Schureman, 1941*) are illustrated in Table 1.

Table 1. Principle harmonic constituents of the tides.

Species and name	**Symbol**	**Period Solar hours**	**Relative Size**
Semi-diurnal:			
Principal lunar	M_2	12.42	100
Principal solar	S_2	12.00	47
Larger lunar elliptic	N_2	12.66	19
Luni-solar semi-diurnal	K_2	11.97	13
Diurnal:			
Luni-solar diurnal	K_1	23.93	58
Principle lunar diurnal	O_1	25.82	42
Principle solar diurnal	P_1	24.07	19
Larger lunar elliptic	Q_1	26.87	8
Long period:			
Lunar fortnightly	M_f	327.9	17
Lunar monthly	M_m	661.3	9
Solar semi-annual	S_{sa}	4383	8
Solar annual	S_a	8766	1

The "relative size" column in Table 1 represents values from equilibrium theory presented by *Schureman* (1941) in his Table 2, expressed as a percent of M_2. Equilibrium theory assumes that the earth is totally water covered and does not consider frictional effects on tidal water motions. It is a simplified method to describe mass tidal characteristics. In addition, *Schureman's* Table 14 presents information on the effect of the longitude of the moon's node. His Table 14 shows that each of the above coefficients are gradually modulated over an 18.6 year cycle, and provides a coefficient which is a function of the year and multiplies the above coefficients to account for the regression of the nodes. The use of the constituents $(M, S, N, K)_2$, $(K,O,P)_1$, qualitatively illustrated in Figure 8, will generally be sufficient to predict the astronomical tide signal to about 90% at tide stations exposed to open ocean conditions. The difference between the astronomical tide signal and the water level measurements is generally attributable to the effects of local meteorological conditions. However, at different locations different constituents dominate, each site is different, and the relative size values from Table 1 above should not be used indiscriminately.

TIDAL PREDICTIONS

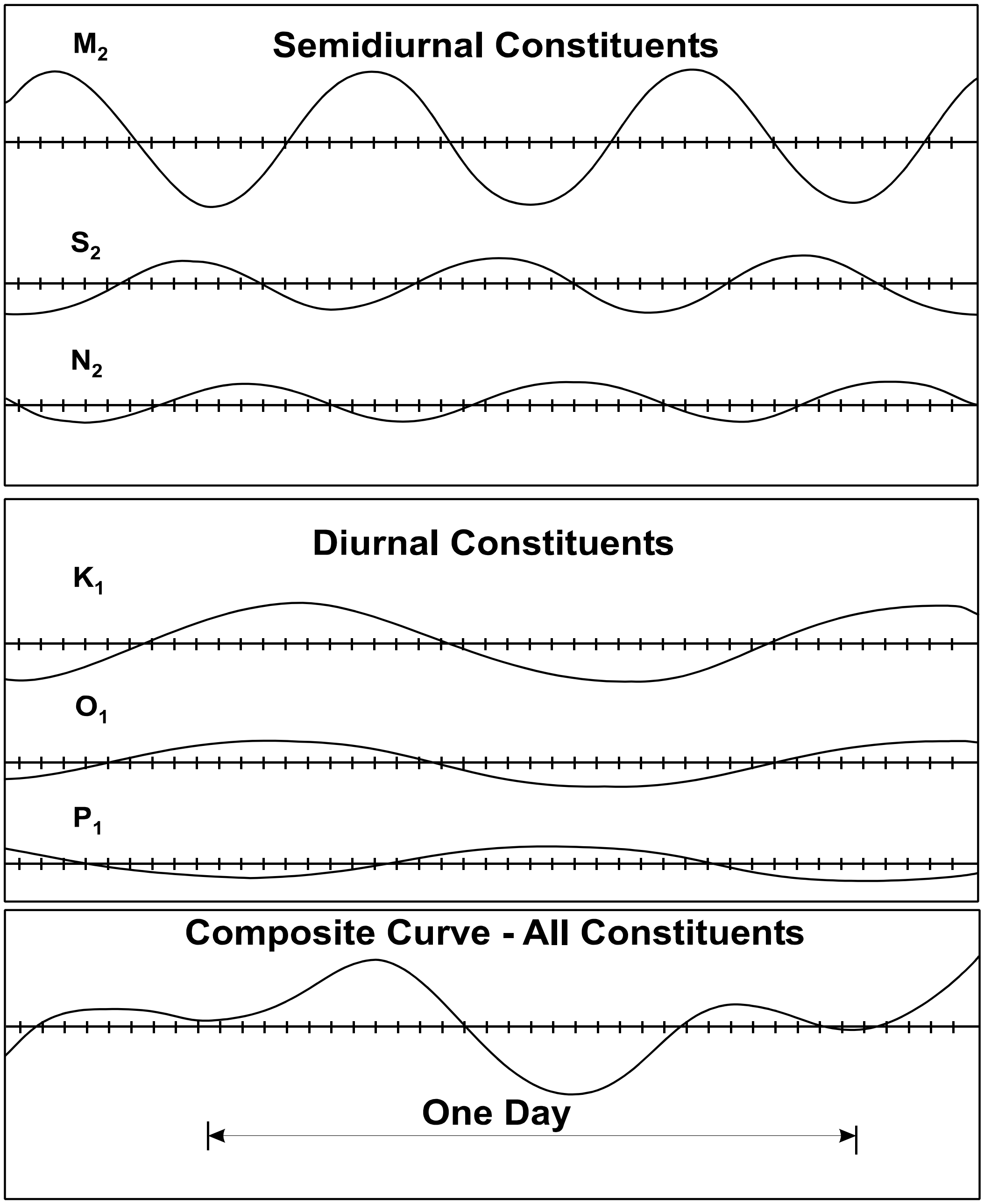


Figure 8. An illustration of the principle harmonic constituents of the tides. The periods and relative sizes of the constituents from Table 1 are suggested. The bottom panel qualitatively illustrates the result of summing the constituents to reconstruct the astronomical tidal component of water level measurements.

Other Signals in Water Level Measurements

Tides are not the only factor causing the sea surface height to change. Additional factors include waves and wind setup; ocean and river currents; ocean eddies; temperature and salinity of the ocean water; wind; barometric pressure; seiches; and relative sea level change. All of these factors are location dependent, and contribute various amounts to the height of the sea surface. Examples are: wind setup and seiche - up to about 1 meter (~3.2 feet); ocean eddies - up to about 25 centimeters (~0.8 foot); upper ocean water temperature - up to about 35 centimeters (~1.1 foot); ocean currents or ocean circulation - about 1 meter; and global sea level rise (about 0.3 meter (1 foot) per century).

Oceanographers, when determining tidal datums, use averaging techniques over a specific time period, the *tidal epoch* of 19 years. As mentioned, 19 years is used because it is the closest full year to the 18.6-year node cycle, the period required for the regression of the moon's nodes to complete a circuit of 360˚ of longitude (*Schureman, 1941*). Referring to Figure 1, the average of all the observed higher high waters over a specific 19 year period (i.e., a NDTE) is defined as the tidal datum *mean higher high water(MHHW)*. As suggested in Figure 1, MHHW will have a specific height, which is not necessarily equal to any higher high water observed during a given tidal day. The averaging technique defines a reference plane from which all the fluctuations in the sea level discussed here, except for global sea level change, have been removed. Thus, the policy of NOS is to consider a new tidal datum epoch every 20 to 25 years to appropriately update the tidal datums to account for the global sea level change and long-term vertical adjustment of the local landmass (e.g., due to subsidence or glacial rebound).