Understanding Tides

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Figure 1.—The Moon's and the Sun's gravitational tugs on the Earth cause the oceans to bulge in two places. As the Earth turns on its axis, the ocean bulges and lows rise and fall along coastlines as daily tides. In these two views of the Newport, Oregon, harbor (photographed seven hours apart on the same day), the fall and rise of the tide show in the relative heights between the floating boats and docks against the fixed pilings and shore objects.

The tide is the periodic daily or semi-daily fluctuation of the sea surface. Ocean tides occur worldwide, but the degree of fluctuation varies from imperceptible to many meters.

The first documented reference to tides was m the fifth century B.C. by the Greek historian, Herodotus, who observed characteristics of the tide in the Red Sea. In the next century, Pytheas noted that the motion of the Moon and the rise and fall of the tide were related. Apparently this observation was an outgrowth of his travels to the British Isles, where the range of tide is many times that of his native Greece.

As human horizons expanded, knowledge of physical sciences and, thus, understanding of tides also increased. From the first, tides have been considered important to navigation. Knowledge of tides was essential for growth and development of coastal communities that flourished as a result of early commerce. Wharves, buildings and other structures had to be constructed with the ever-changing water level in mind (figure 1) .

Today, it is even more important that complicated but rhythmic tidal motions and their associated forces be understood as we build closer to the waterfront or shore. Bridges and pipelines connect points of land once considered inaccessible. Bays and harbors have to be protected from the forces of the sea, of which the tide is a major contributor. Supertankers, no longer able to enter many existing ports, have to be handled on the continental shelf, requiring deepwater loading facilities in exposed areas. Consequently, we need to understand not only tides in coastal areas, but also those of the open ocean.

As people seek to better manage the wastes they dump into streams, rivers, and estuaries, they are calling on oceanographers for more information concerning estuarine and coastal circulation. This is essential for establishing intelligent but practical waste management procedures. Tides play an important role in determining rates of dilution, mixing, and flushing of these coastal waters.

Defining seaward boundaries is another issue with relevance for tide knowledge. In the offshore oil industry, for example, state-Federal boundaries must be precisely defined for determining which jurisdiction may claim taxable revenue. Similarly, as in past years along the Oregon coast, private-state boundaries are becoming critical issues. Since the coastline is not static and instead is constantly undergoing change, boundaries are difficult to demarcate. As a result, boundaries are defined in relation to mean tide elevations.

To help keep track of these mean tide elevations and use them, certain standard references have been established. The most effective references are the tidal datums, which are simply fixed references from which we reckon heights or depths. There are a variety of such datums, called by different names, such as mean low water, mean lower low water, mean high water, mean higher high water, and mean sea level. Each of these tidal datums may be determined in relation to a time period of a specified length, called a tidal epoch. These tidal datums can be located on the ground and mapped (figure 2).

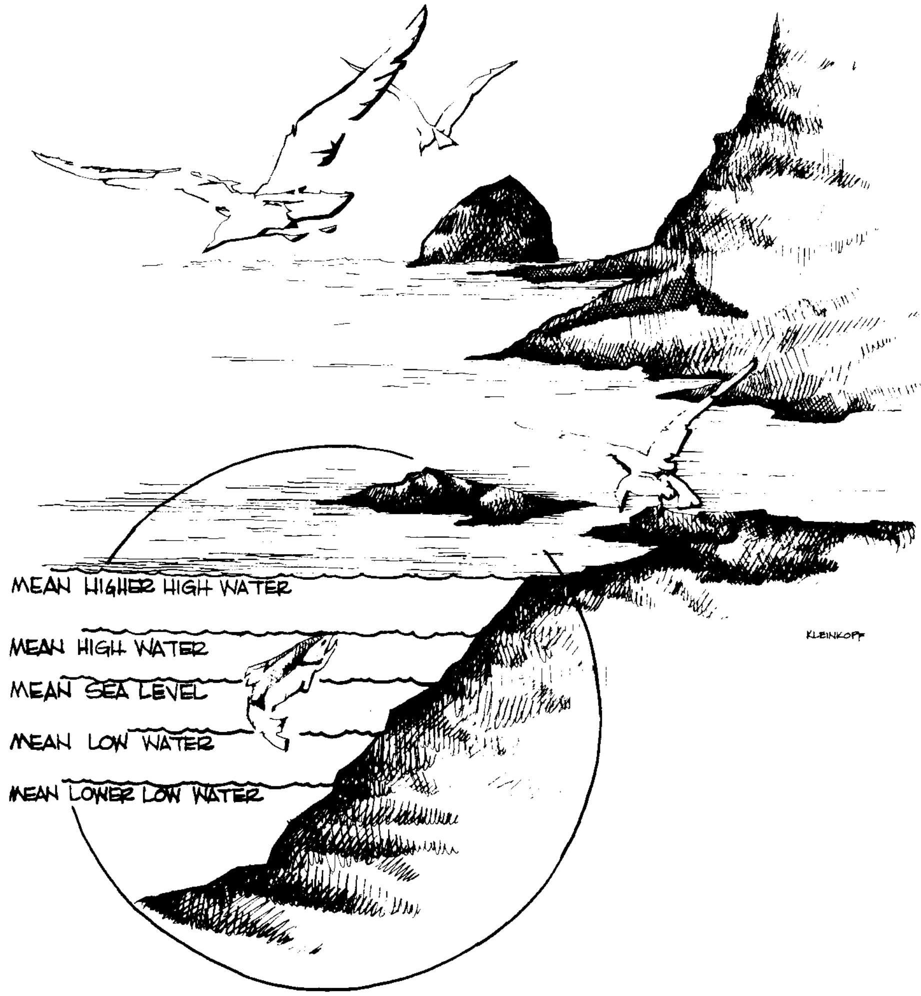

Figure 2.—The height of the ocean's surface rises and falls with predictable regularity. The means of these periodic high- and low-water conditions are defined as tidal datums. The tidal datums are relative (that is, related to one another) and identified as shown to the left.

Elementary tidal theory — the equilibrium tide

The cause-and-effect relationship between the Moon and tides remained a mystery until 1687, when Isaac Newton published his classic book, Philosophiae naturalis principia mathematica, which stated his laws of gravity. Newton's work, along with that of Daniel Bernoulli in 1740, led to the equilibrium theory of tides—a basis for understanding simple tidal generation.

The Moon as primary force. Although a number of forces act to produce tides, for the moment we will consider only the forces caused by the Moon. Newton's law of gravitation states that two bodies are attracted toward each other. The strength of this attraction depends on the mass of the bodies and the distance between them. (Two bodies are attracted directly proportional to the products of their masses and inversely proportional to the square of the distance between them.) In the case of the Earth and the Moon, the gravitational attraction between the two is balanced by an additional force. The balancing force is the centrifugal force caused by the rotation of the Earth and the Moon about the center of mass of the Earth-Moon system.

On the side of the Earth nearer the Moon, the gravitational attraction between the Earth and the Moon is greater than the centrifugal force. On the side of the Earth farther from the Moon, the centrifugal force is greater than the gravitational attraction between Earth and Moon. Thus, the tide-generating forces try to create two tidal "bulges" on opposite sides of the Earth along a line connecting the Earth's center and the Moon's center. Because there are two bulges, there are generally two tides per lunar day (figure 3).

Figure 3.—The two tidal "bulges" are present on opposite sides of the Earth, formed by the difference between the gravitational forces and the centrifugal force caused by the Earth's revolution around the center of mass of the Earth-Moon system. The Earth makes one complete rotation relative to the moon every 24 hours and 50 minutes. Thus, a location on a coast moves through each of the ocean bulges in a lunar day, and there are two tides a day along most coasts.

The Sun as secondary tidal force. Heavenly bodies other than the Moon cause tide-generating forces, but the only other body of significance is the Sun. Although it has far greater mass than the Moon, the Sun is much farther from the Earth than the Moon. Consequently, the Sun's tide-generating force on Earth is only about 46 percent as great as that of the Moon.

To understand the variations in tides as they occur over extended periods of time, consider the constantly changing relationship of the Earth, the Moon, and the Sun. Remember that the Moon orbits about the rotating Earth, and both the Earth and the Moon orbit about the Sun. In addition, remember that they do so not in perfect circles, but in ellipses, so that distances one from the other are constantly — and predictably — changing.

Remember that the Earth's axis is tilted with respect to its orbit about the Sun, and the Moon's orbit is also at an angle to the Earth's orbit. Therefore, the angular relationships between the Earth and the Moon, and the Earth and the Sun, are constantly — and predictably—changing. Now let's look at the effects of all these dynamic relationships.

The Moon and the Sun interact. Anyone who has observed tides or studied a tide table has noted that the difference between a high tide and a low tide may be greater at one time of the month than at another. The range of tide, or difference between successive high and low waters, varies primarily as a result of the changing positions of the Sun and Moon with respect to the Earth.

Figure 4 reminds us that as the Moon rotates about the Earth approximately once a month, it is aligned with the Sun twice a month and it is at right angles (quadrature) at two other times during the month.

When the Moon is on a line connecting the Earth and the Sun, we have either a new Moon or a full Moon. At this time the attractive forces of the Sun and the Moon are aligned and reinforce each other, increasing the tidal bulge. When this occurs semimonthly, the range is increased, with the high tides being higher and low tides being lower than average. These are called spring tides (this name implies no reference to the season of the year).

When the Moon is at quadrature, we have either a first-quarter or a third-quarter Moon. At this time the attractive forces of the Sun and the Moon are at right angles and tend to counteract one another, resulting in a decreased tidal range: high tides are lower and low tides are higher than average. These are called neap tides.

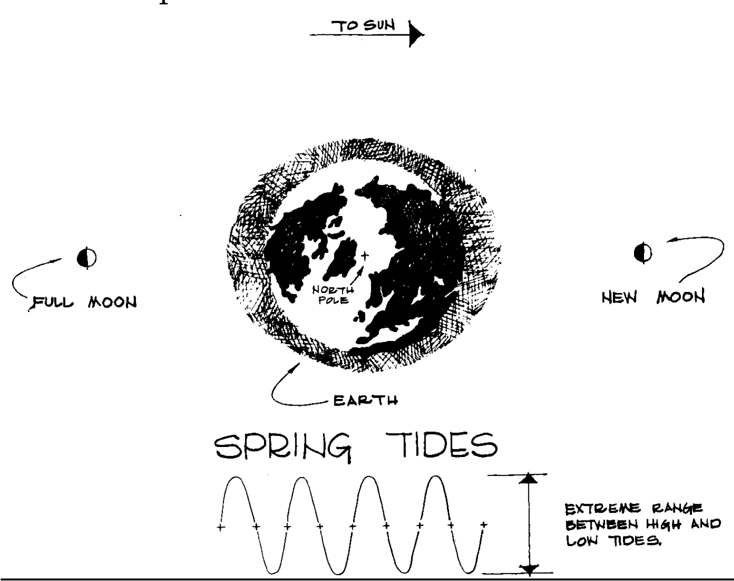

Figure 4a.—During times of full and new Moon, the Earth, Sun, and Moon are in a line; and spring tides occur.

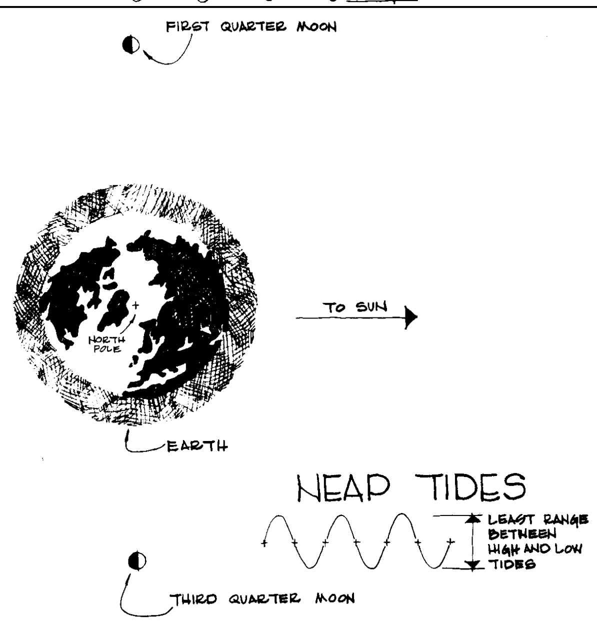

Figure 4b.—When the Moon is at first and third quarter, the Moon and Sun form a right angle with the Earth; neap tides now occur.

Effects of elliptical orbits. As the Moon moves through its elliptical orbit about the Earth approximately once each month, it passes through points nearest and farthest from the Earth. Figure 5 illustrates this phenomenon. The point nearest the Earth is called perigee; that farthest from the Earth, apogee. Tide range is increased when the Moon passes through perigee. The tide range is decreased at apogee.

As the Earth moves about the Sun, a similar situation occurs. The point when the Earth is nearest the Sun is perihelion; farthest from the Sun, aphelion. The effect of the Earth's passing through perihelion and aphelion is less pronounced than the counterparts of the Moon's motion but is of the same sort. And, of course, it occurs on a yearly basis instead of monthly.

The angular relationship. As noted previously, we observe a changing angular relationship between the Earth and the Moon, and the Earth and the Sun. The angular distance north or south of the equator is called declination. The changing declination of the Moon and the Sun also play an important role in modifying tides.

The Moon's declination completes a full cycle approximately every 27 1/3 days. In completing this cycle, it can reach maximum values of nearly 28.6° north and south of the equator.

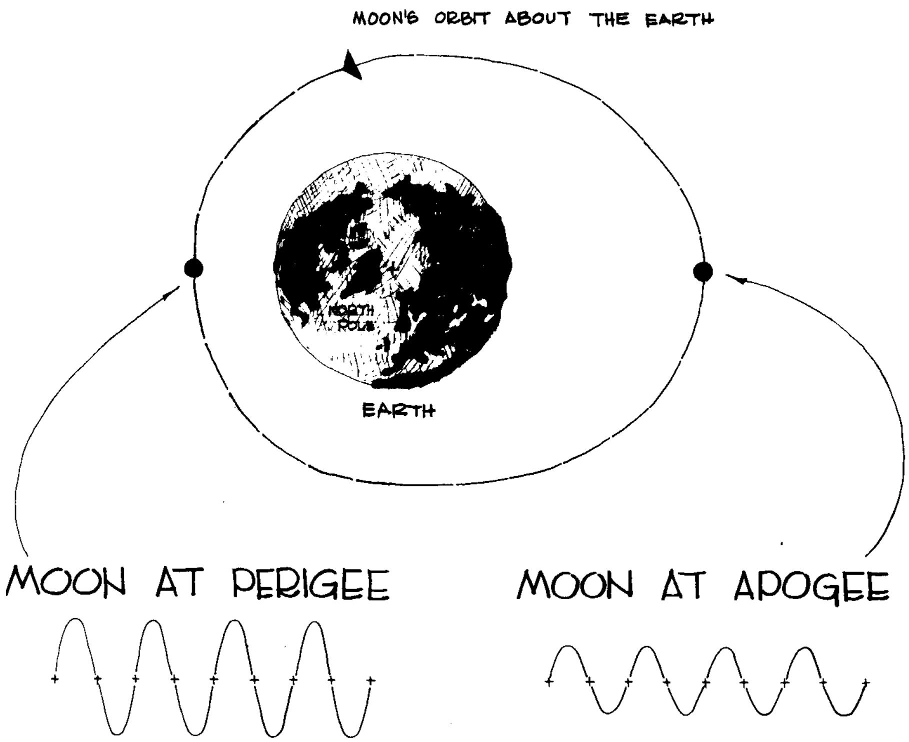

Figure 5.—Elliptical path of the Moon orbiting the Earth. Tidal range is greater when the Moon is at perigee than when it is at apogee.

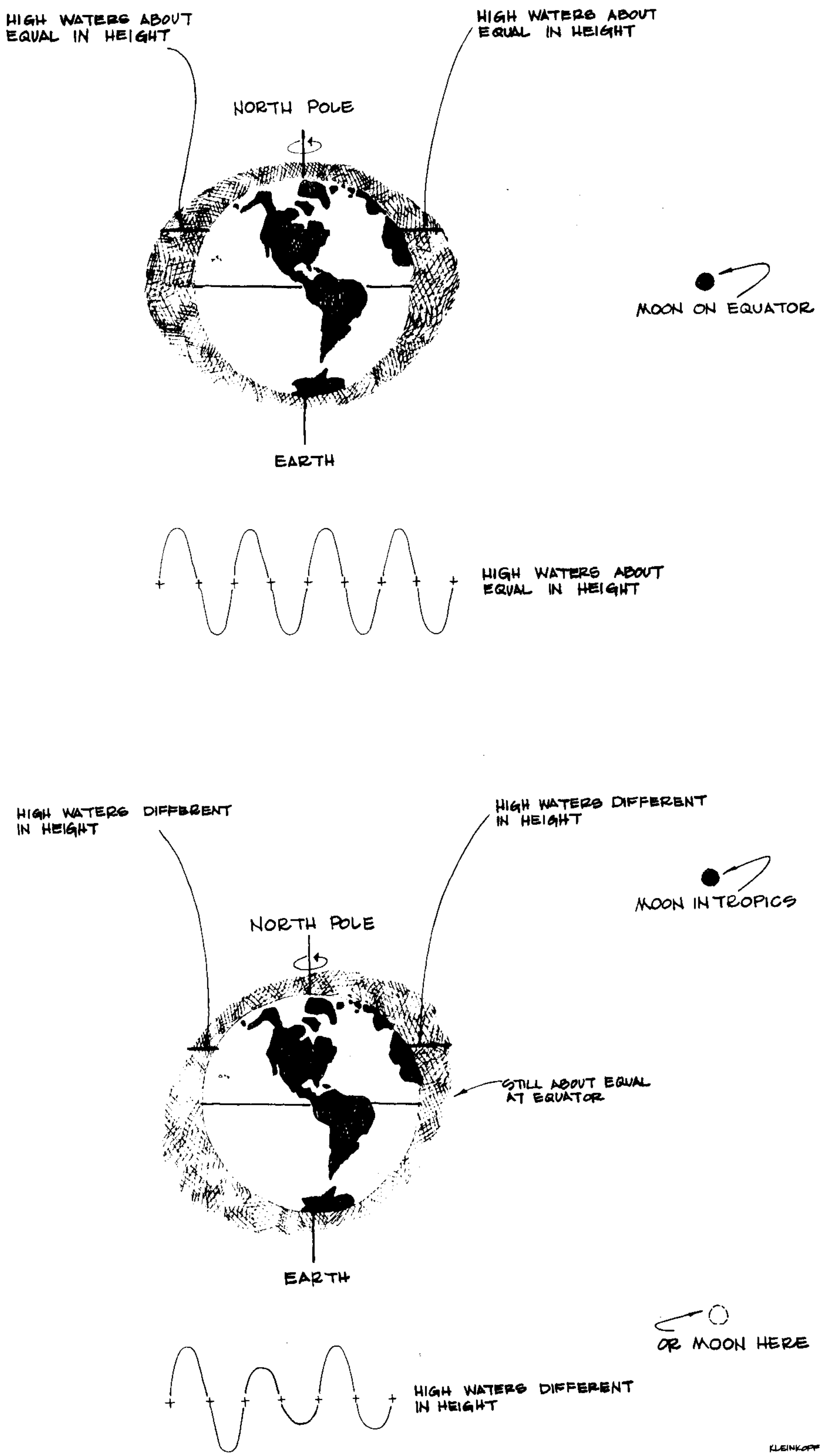

Figure 6.—The difference in height of each day's two high quarters or of its two low waters increases as the Moon moves (declines) toward the Earth's north or south pole. This difference, called diurnal inequality, is generally greatest when the Moon is at maximum declination.

As the Moon approaches its maximum declination (once north and once south each cycle), its attractive force is unevenly distributed with respect to the equator, as shown in figure 6. The effect is to cause a difference in the heights of succeeding high waters and succeeding low waters in the same day. The difference between high waters and between low waters is known as diurnal inequality (diurnal means "daily ") .

Diurnal inequality is generally at a maximum when maximum declination occurs, producing what are called tropic tides. Diurnal inequality is at a minimum when the Moon is over the equator, causing equatorial tides. As one would expect, tropic and equatorial tides each occur twice every cycle of 27 1/3 days.

Interaction. Of course, all of these astronomic movements go on simultaneously in cycles whose lengths vary one from the other. Thus, their combined effects may be to enhance or nullify one another. In a later section, we will note how all combine to affect clamming tides in Oregon.

The real tide varies from theory. In discussing equilibrium theory, we assumed the Earth was a smooth surface completely covered by a fluid in equilibrium with the tide generating forces. We ignored the effects of friction in the movement of fluid, inertia, depth of the ocean, presence of continents, and rotation of the Earth. Of course, all of these factors must be considered when we study the tides as they really are. If equilibrium assumptions were valid, tidal response would be simultaneous with the tide-producing forces.

Because this is not the case, the time of high tide varies considerably throughout the world's oceans in relation to when the Moon passes over the local meridian. (A meridian is a great circle of the Earth passing through the poles and any given point on the Earth's surface.) The height of tide also cannot be explained entirely by the simplified theory. Consequently, equilibrium theory does not fully account for the observed tidal phenomena. Instead it only gives us insight into the basic causes and fluctuations.

Predicting tides. When we deal with nature, one of our prime objectives is to predict future events. Tides are no exception. In predicting the behavior of the ocean, we generally can predict tides better than any other natural phenomenon, at least in coastal areas where knowledge of the tides is most essential.

Our ability to predict tides is good not because we understand the theory of tides better than that of other oceanic events, but because the tide is determined by the Sun and Moon, movements of which are well-ordered in time and space.

The *marigram*, or graphic record of the rise and fall of the tide, at a given location, is a continuous function that is periodic, readily lending itself to a curve-fitting procedure and thus a forecast of tidal heights.

Types of tide

A marigram is distinctive for a specific location, but there are general characteristics of the tides throughout the world that permit us to establish a classification system. Figure 7 shows examples of marigrams for diurnal, semidiurnal, and mixed types.

Diurnal. A tide is diurnal if, during the period of a lunar day (of 24 hours and 50 minutes), there occurs only one high water and one low water. Diurnal tides are primarily caused by the changing declination of the Moon and are most pronounced at the times of maximum declination (figure 6). These tides are found in the northern Gulf of Mexico and in southeast Asia.

Semidiurnal. The semidiurnal tide is that which is most commonly found throughout the world. It is characterized by two high waters and two low waters in the lunar day. The elevations of succeeding high waters and succeeding low waters are nearly the same. A semidiurnal tide is found on the East Coast of the United States, for example.

Mixed. Just as with a semidiurnal tide, the mixed tide is marked by two high waters and two low waters in a lunar day. Succeeding high waters, low waters, or both are generally different in height, however. These differences are known as diurnal inequality. Remember the inequality is caused by the changing declination of the Moon. Mixed tides are common to the West Coast of the continental United States, Alaska, and Hawaii.

Phenomena associated with tides Marigrams may show changes in water level that are not due solely to tidal movement caused by heavenly bodies. Among these tidal phenomena are meteorological effects. Also, in any discussion of tides the related horizontal movement of water, or tidal currents, should be mentioned.

The meteorological effects. Water responds to external forces applied to it. Two forces always at work in varying degrees on the water surface are wind and direct barometric pressure. They combine to effect a change in the elevation of the water surface known as wind setup or storm surge.

In coastal areas where the water is shallow, wind interacts with water at the surface and as a result moves the water from one area to another. It is not easy to say exactly how a water body will respond because the effects are determined by wind speed, duration, and distance over which the wind blows (fetch), as well as by such other complicating factors as topography and stage of the tide.

It is generally true in coastal areas, however, that the water surface will respond directly to the wind. Thus, a wind blowing toward shore will tend to raise the water level on the coast and wind blowing away from shore, to decrease it.